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RESEARCH ARTICLE

Analysis of Transformer Oil Condition of Dissolved Gas Analysis Testing Results with Modified Conventional Methods

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Abstract

Power transformers are one of the most widely used important components in the electric power system. Dissolved Gas Analysis (DGA) testing is used to diagnose transformer failures before more severe damage occurs by analyzing gas indicators dissolved in transformer oil through several methods, one of which uses conventional methods. However, based on most of the tests conducted by researchers, the detection accuracy of the conventional method is still quite low, and can result in an undetermined state. This research has the main objective of identifying the weaknesses of one of the conventional methods, namely the Rogers Ratio method. This research uses modifications to the fault diagnosis workflow of the Rogers Ratio method, which is then applied in the interpretation of DGA test results on power transformers. Based on the results of this research, the conventional Rogers Ratio method cannot diagnose the fault (undetermined), while the modified version can diagnose the fault with a temperature classification of 150 °C to 200 °C. When compared with other conventional methods such as the widely used Duval Triangle method, the diagnosis found that the fault has a temperature classification of less than 300 °C. Therefore, the results of the modified interpretation of the Rogers Ratio method are better than before, as well as in line and more specific to that of the conventional Duval Triangle method and can be applied as an additional technique for interpreting DGA test data.

Keywords: Conventional Method, Dissolved Gas Analysis, Duval Triangle, Rogers Ratio, Transformer

1. Introduction

Power transformers are one of the most important and expensive components in the power system [1]. This component is necessary to be maintained for reliability in meeting high electricity demand. A failure in transformer operation requires expensive repair costs and long downtime to carry out the repair [2]. Therefore, it is beneficial for transformer operators to find signs of failures before the actual failure happens. The Dissolved Gas Analysis (DGA) method is a method used to diagnose the types of failures that may occur in power transformers during operation [3]. This method analyzes the gases dissolved in the transformer oil to identify the condition of the transformer in the form of failure. These gases include Methane (CH_4), Ethylene (C_2H_4), Acetylene (C_2H_2), Ethane (C_2H_6), Carbon Dioxide (CO_2), Carbon Monoxide (CO), Oxygen (O_2), Hydrogen (H_2) and Nitrogen (N_2) [4].

Conventional methods for DGA diagnosis that are often used include Total Dissolved Combustible Gas (TDCG), Rogers Ratio, and Duval Triangle [5]. However, these methods have different drawbacks for diagnosing the occurrence of faults in transformers [6]. Several researchers have utilized these conventional methods of DGA diagnosis. The authors of [7] and [8] utilized transformer failure using transformer oil samples, where both researches can conclude the thermal fault temperatures using all three conventional methods mentioned above. However, research in [9] shows that the Rogers Ratio method returns a conclusion of undetermined fault in the transformer. This indicates that there is still a problem in the Rogers Ratio method which needs to be solved for such analysis to be properly utilized.

This research will discuss the analysis of DGA test results that compares the interpretation of the original Rogers Ratio method with the modified one. The case study that will be applied to DGA testing and interpretation is one of the power transformers located in Manokwari, Papua province. The main contributions of this paper are providing the advantages and effectiveness of the modified Rogers Ratio method in diagnosing disturbances in power transformers, and determination of the transformer's conditions based on the DGA test results. The remaining of this paper is organized as follows: Section 2 describes the basic understanding of the DGA methods, Section 3 outlines the methodology used in this research, Section 4 describes the analyses for each test results, and the research is concluded in Section 5.

2. Dissolved Gas Analysis (DGA)

2.1 Transformer Oil

Transformer oil is composed of a complex mixture of hydrocarbon molecules containing molecular bonds. These gas molecules can be classified into two types, i.e. combustible gas and non-combustible gas. These gases consist of Hydrogen (H-H), Methane (CH_3–H), Ethane (CH_3–CH_3), Ethylene (CH_2 =CH_2), and Acetylene (CH≡CH), which are known as combustible gases or fault gases. While several other gases such as Carbon Monoxide (C≡O), Carbon Dioxide (O=C=O), Oxygen (O=O), and Nitrogen (N≡N) are known as non combustible or non-flammable gases. This gas will later form at a certain temperature and dissolve in the transformer oil. The formation of these transformer oil-soluble gases will begin at varying temperatures. H_2 and CH_4 gases begin to form in relatively small amounts at 150 °C, while C_2H_6 gas forms at around 250 °C, C_2H_4 at 350 °C, and C_2H_2 gas between 500 °C and 700 °C. The amount of concentration of these gases will change as the temperature increases. With the increase of temperature, the production of CH_4, C_2H_6 and C_2H_4

production decreases. However, CH_4 production exceeds H_2 at temperatures between 200 °C and 300 °C, while C_2H_6 production begins to exceed CH_4 at 275 °C. Then, at temperatures between 450 °C and 800 °C H_2 production increases over the other gases along with an increase in the amount of C_2H_2 at 700 °C.

2.2 Failure Types of Transformer Oil

Disturbances in power transformers that cause dissolved gas in transformer oil can be categorized into several types, i.e. thermal disturbance and electrical disturbance.

2.2.1 Thermal Disturbance

Thermal disturbance is caused by excessive heat in the transformer components. The heat is caused by various factors such as excessive load, insulation damage, or cooling system failure. This disturbance can be classified further into several classes based on temperature range, namely:

1. Thermal Fault (T3)
   This is a thermal disturbance that occurs at temperatures above 700 °C. In this condition, C_2H_4 production begins in relatively high quantities. This disturbance is evidenced by the carbonization of oil, metal coloring (at 800 °C), and metal melting (below 1,000 °C).
2. Thermal Fault (T2)
   This is a thermal fault that occurs at temperatures between 300 °C and 700 °C. This fault produces high amounts of C_2H_6. This fault commonly appears in oil and paper which results in carbonization of the paper.
3. Thermal Fault (T1)
   This is a thermal fault that occurs at temperatures below 300 °C. In this fault, CH_4 production becomes the dominant factor in fault gas indication. This fault can turn insulating paper into a brownish color.

2.2.2 Electrical Disturbance

Electrical disturbance are faults caused by excessive or abnormal electric current in the power transformer. This excessive electric current is caused by various factors, such as short circuit, overvoltage, or damage to certain components. There are several classifications in electrical disturbance, namely:

1. Partial Discharge (PD)
   PD is the local penetration of electric charge in liquid insulation such as oil, or solid insulation such as winding isolation. In oil insulation, this disturbance can arise due to air bubbles trapped in the transformer oil. Whereas in solid insulation, partial discharge appears in the void or air cavity between two conductors. In transformer oil, PD conditions cause H_2 gas to rise. Whereas in insulation such as cellulose, PD causes the generation of H_2, CO, and CO_2.
2. Low Energy Discharge (D1)
   This disturbance will release a small portion of energy in the form of a spark. In this condition, the gases produced are H_2 and CH_4. This will cause disturbances

in the form of carbonization of insulation paper to become black or brownish and can cause holes in the insulation paper.

3. High Energy Discharge (D2)
   This disturbance usually appears in oil and paper which is indicated by large damage and carbonization of paper. Some cases of this fault can cause tripping of power transformers. D2 faults also cause the production of high amounts of C_2H_2 and H_2 gas.

2.3 Dissolved Gas Analysis Testing Method

The Dissolved Gas Analysis (DGA) method is used to diagnose the condition of a transformer based on the amount of dissolved gas in the transformer oil.

The DGA method is one of the first indicators in identifying insulation and oil deterioration, overheating, partial discharge, and arcing. This method will provide information on the quality of the overall transformer oil condition. The DGA method test is carried out by taking oil samples from the transformer unit and then extracting the dissolved gases in the oil. The extracted gases are separated, the individual components are then identified, and the quantity is calculated in units of parts per million (ppm) through the gas chromatography method. The gases consist of fault gases such as H_2, CH_4, C_2H_6, C_2H_2 and C_2H_4. The data will then be analyzed through several existing interpretation methods to get the results of fault detection in power transformers.

There are several techniques or methods of interpreting DGA test results. The conventional method of DGA test interpretation is in the form of comparing the ratio of gases in transformer oil or through visualization data. Each of these methods has different calculation methods to get the results of power transformer diagnosis. Conventional methods of DGA test results include the Total Dissolved Combustible Gas (TDCG) method, Rogers Ratio method, and Duval Triangle method.

2.3.1 TDCG Interpretation Method

The TDCG method is used to determine the initial condition of transformer oil based on the amount of dissolved gas in the transformer oil sample. Table 1 describes the concentration limits for dissolved gas in ppm.

Table 1. TDCG Dissolved Gas Concentration Limits in parts per million (ppm) [6]

Status	Condition 1	Condition 2	Condition 3	Condition 4
H_2	100	101-700	701-1800	> 1800
CH_4	120	121-400	401-1000	> 1000
C_2H_2	35	36-50	51-80	> 80
C_2H_4	50	51-100	101-200	> 200
C_2H_6	65	65-100	101-150	> 150
CO	350	351-570	571-1400	> 1400
CO_2	2500	2500-4000	4001-10000	> 10000
TDCG	**720**	**721-1920**	**1921-4630**	**> 4630**

The following is an explanation of the operational classification of transformers based on the TDCG method, which is divided into four conditions, namely:

1. Condition 1, indicating the transformer is operating normally but further monitoring of the condition of these gases by other interpretation methods is still required.
2. Condition 2 indicates the presence of combustible gas levels in greater than normal amounts. At this level there is a possibility of failure symptoms that should be recognized. More regular oil sampling is required.
3. Condition 3 indicates decomposition of the insulation paper and/or transformer oil. One or more failures may have already occurred in the transformer. This condition requires the power transformer to be cautioned and further maintenance is required.
4. Condition 4 indicates excessive decomposition or widespread damage to the paper insulator or transformer oil. Continued operation may result in transformer failure, thus additional inspection is required.

2.3.2 Rogers Ratio Interpretation Method

The Rogers Ratio method is a method that complies with the IEEE C57.104 standard. However, it only considers three gas concentration ratios. These gas ratios are chosen according to existing experience in the industry in detecting faults in transformers. Figure 1 shows the flowchart of the Rogers Ratio method. The composition of input gas is quantified to then compared using a ratio between different molecules. The ratios are:

- R1, which is the ratio between the concentration of CH_4 and H_2;
- R2, which is the ratio between the concentration of C_2H_2 and C_2H_4;
- R3, which is the ratio between the concentration of C_2H_2 and CH_4;
- R4, which is the ratio between the concentration of C_2H_6 and C_2H_2; and
- R5, which is the ratio between the concentration of C_2H_2 and C_2H_6.

The ratios are then used to determine the probable case of failure that happens at the source of the input gas. There are 6 cases ranging from Case 0 with no faults, up until Case 5, which indicates a thermal failure of more than 700 °C.

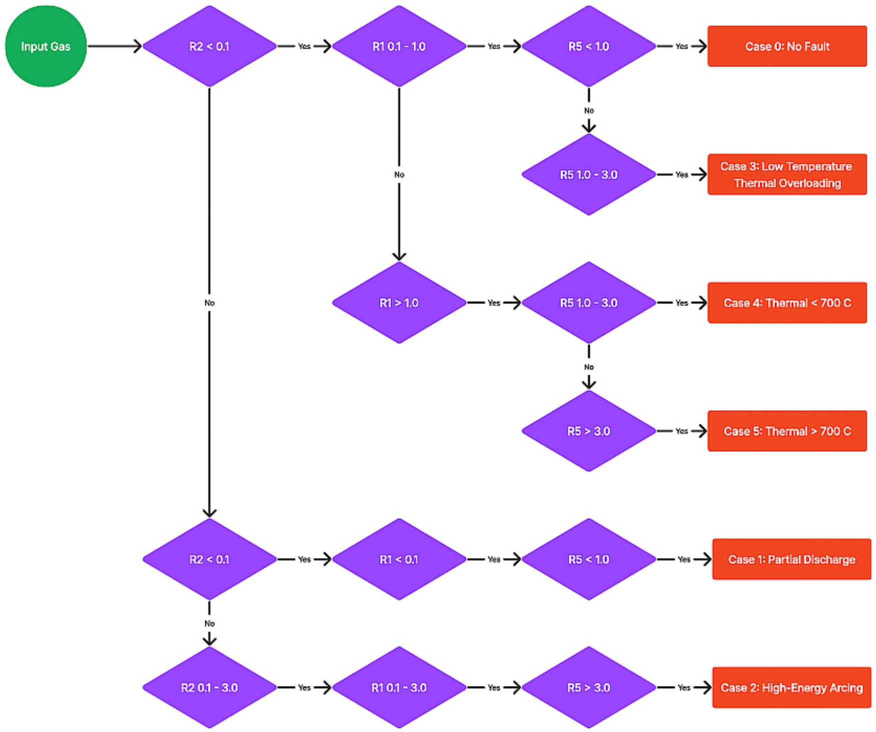

Figure 1. Flowchart of the Rogers Ratio Method [6]

2.3.3 Duval Triangle Method

The Duval Triangle method was invented by Michel Duval in 1974. The specific conditions considered are the concentrations of CH_4, C_2H_4, and C_2H_2. In the Duval Triangle method, the total of these three gases is expressed as 100%. Changes in the composition of these three gases indicate a disturbance that occurs in a transformer.

The failure analysis using Duval Triangle method involves the calculation between the compositions of CH_4, C_2H_4, and C_2H_2, using equations (1) and (3):

$$\%CH_4 = [CH_4/(CH_4 + C_2H_4 + C_2H_2)x100\%] \quad (1)$$

$$\%C_2H_4 = [C_2H_4/(CH_4 + C_2H_4 + C_2H_2)x100\%] \quad (2)$$

$$\%C_2H_2 = [C_2H_2/(CH_4 + C_2H_4 + C_2H_2)x100\%] \quad (3)$$

Furthermore, the percentage of each gas is mapped on the Duval Triangle, where the point of intersection between the lines of the gases indicates the condition and type of disturbance that occurs in the transformer. The triangle can be seen in Figure 2, while the description of each failure indicated by the portion of area in the triangle is described in Table 2.

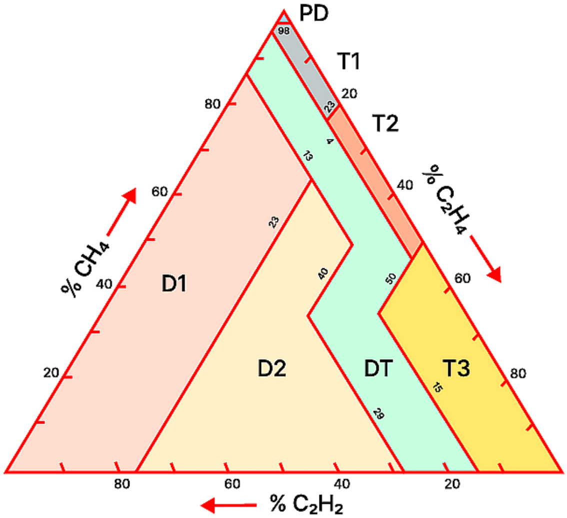

Figure 2. Interpretation of the Duval Triangle Method [10]

Table 2. Disturbance Type of Duval Triangle Method [10]

Zone	Fault Diagnosis
PD	Partial Discharges
D1	Low-Energy Discharge
D2	High-Energy Discharge
T1	Thermal Faults < 300 °C
T2	Thermal Faults Between 300 °C – 700 °C
T3	Thermal Faults > 700 °C

3. Research Methodology

This research was conducted on power transformers located at the Manokwari Gas Engine Power Plant (GEPP). The data obtained is the DGA test result data of Generator Step Up Transformer (GSUT) #1 11/20 kV of Manokwari GEPP. The flowchart of the methodology of this research can be seen in Figure 3. The research phase begins with collecting data in the form of transformer oil concentration. Then, the research continued by identifying the diagnosis of interference with the DGA test results using the interpretation standard. These standards include conventional DGA interpretation methods that will be used, i.e. TDCG, Rogers Ratio and modified Rogers Ratio method, and as a comparison the Duval Triangle method is also used.

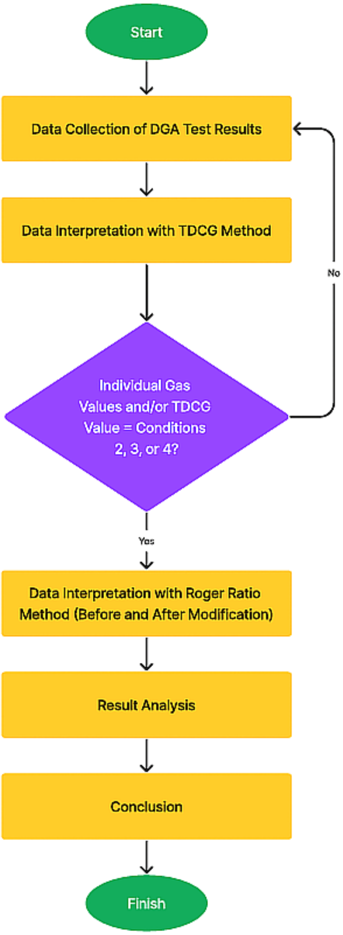

Figure 3. Research Flow Chart

3.1 Specification of Transformer Under Test

The specifications of the transformer to be tested can be seen in Table 3.

Table 3. Specification of Manokwari GEPP GSUT #1 Power Transformer

Specification	Description/Value
Manufacturer	Bambang Djaja
Nominal Voltage	11 / 20 kV
Capacity	12.5 MVA
Frequency	50 Hz
Year of Manufacture	2018

3.2 DGA Transformer Oil Concentration Data

The DGA test results for the transformer oil used in the transformer under test is described in Table 4.

Table 4. DGA Test Results of Manokwari GEPP GSUT #1

No	Type of Gas	Concentration (ppm)
1	Hydrogen (H_2)	25
2	Methane (CH_4)	245
3	Acetylene (C_2H_2)	0.2
4	Ethylene (C_2H_4)	18
5	Ethane (C_2H_6)	429
6	Carbon Monoxide (CO)	456
7	Carbon Dioxide (CO_2)	3968

4. Results and Discussion

4.1 Result Interpretation using TDCG Conventional Method

The TDCG method is one of the DGA interpretation methods based on the total amount of combustible gas in dissolved oil. From the amount of gas concentration, the TDCG value is obtained, and described in Table 5.

Table 5. TDCG Results on DGA Testing of Manokwari GEPP GSUT #1

H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	TDCG	Condition
25	245	0.2	18	429	456	1173.2	Condition 2

The condition of the GSUT #1 of Manokwari GEPP based on the TDCG analysis method is Condition 2, indicating that the level of combustible gas has exceeded the normal limit. Individually, some gas values exceed normal limits (based on Table 1), namely CH_4 and CO gas which are defined under Condition 2, while C_2H_6 gas is defined under Condition 4. The increase in Methane gas (CH_4), Carbon Monoxide gas (CO) and Ethane gas (C_2H_6) indicates that there has been a thermal overload in the internal transformer.

4.2 Interpretation Analysis of Conventional Rogers Ratio Method

Based on the definitions stated in Section 2.3.2., the calculations of the R1, R2, and R5 ratios for the conventional Rogers Ratio method can be seen below:

- R1 = CH_4/H_2 = 245/25 = 9.8
- R2 = C_2H_2/C_2H_4 = 0.2/18 = 0.01
- R5 = C_2H_4/C_2H_6 = 18/429 = 0.04

The obtained ratios are then compared with the Rogers Ratio flowchart seen in Figure 1, where the following results can be obtained and described in Table 6. It can be found that the interpretation result of the Rogers Ratio method is undetermined. This is because the value is outside the ratio limit of the predetermined reference, thus this method is unable to diagnose a disturbance. To fix this, a modified Rogers Ratio method is then proposed.

Table 6. Interpretation Results of Rogers Ratio Method

Ratio	Result
R2	0.1
R1	9.8
R5	0.04
Fault Type	**Undetermined**

4.3 Modified Rogers Ratio Method

The modified Rogers Ratio method is based on Rogers Four Ratios Method described in [11]. This modification involves the addition and/or modification of several ratios between molecules, due to the lack of utilization of different molecule's compositions. This modification is done to increase the accuracy of the diagnosis of the fault that occurs in the transformer than the conventional method, and to ensure that the fault can be defined for all gas ratios. The ratios considered in this method are:

- R1, which is the ratio between the concentration of C_2H_2 and C_2H_4;
- R2, which is the ratio between the concentration of CH_4 and H_2;
- R3, which is the ratio between the concentration of C_2H_4 and C_2H_6; and
- R4, which is the ratio between the concentration of C_2H_6 and CH_4.

The flowchart or flow of diagnosis of the modified Rogers Ratio method can be seen in Figure 4, and the description of each case is described in Table 7. Like the conventional method, the modified Rogers Ratio method is based on the quantification and classification of gas molecule's composition, to then be compared using a ratio between different molecules.

Table 7. Cases of the Modified Rogers Ratio Method

Case	Description
Case 1	No Fault
Case 2	Undetermined
Case 3	Partial Discharge
Case 4	Thermal Fault < 150 °C
Case 5	Thermal Fault Between 150 °C – 200 °C
Case 6	Thermal Fault Between 200 °C – 300 °C
Case 7	Thermal Fault > 700 °C*
Case 8	Thermal Fault Between 300°C – 700 °C
Case 9	Arcing Fault with Low Energy
Case 10	Arcing Fault with High Energy
Case 11	Partial Discharge with Tracking

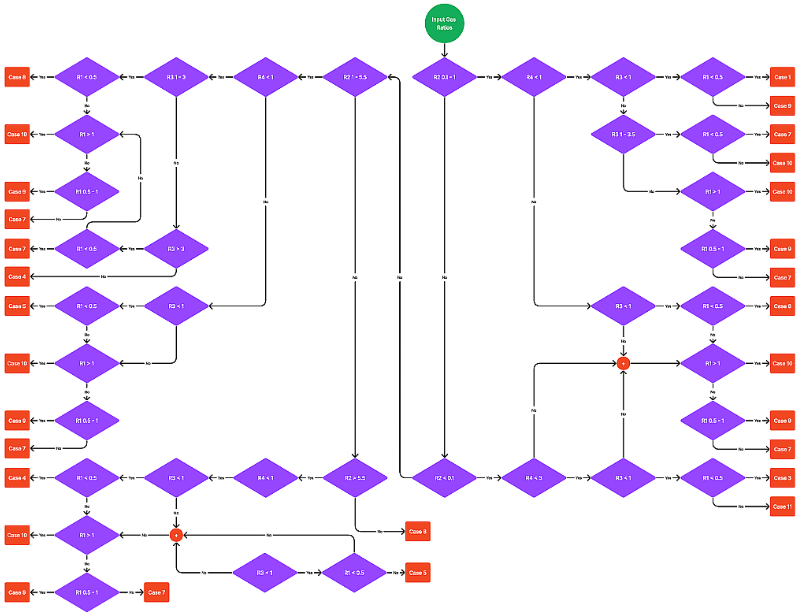

Figure 4. Flowchart of the Modified Rogers Ratio Method [11],[12],[13]

Gas ratio calculation for the modified Rogers Ratio method are as follows:

- R1 = C_2H_2/C_2H_4 = 0.2/18 = 0.01
- R2 = CH_4/H_2 = 245/25 = 9.8
- R3 = C_2H_4/C_2H_6 = 18/429 = 0.04
- R4 = C_2H_6/CH_4 = 429/245 = 1.75

The obtained ratios are then compared with the Modified Rogers Ratio flowchart seen in Figure 4, where the following results can be obtained and described in Table 8. It can be found that the interpretation result of the Rogers Ratio method is Case 5, which is described a thermal fault between 150 °C – 200 °C. Therefore, the modified Rogers Ratio method can define the fault based on the data provided. To confirm the result, an interpretation based on the conventional Duval Triangle method is used.

Table 8. Interpretation Results of the Modified Rogers Ratio Method

Ratio	Result
R1	0.01
R2	9.8
R3	0.04
R4	1.75
Fault Type	**Case 5**

4.4 Duval Triangle Method Interpretation Analysis

The Duval Triangle interpretation method uses a comparison of CH_4, C_2H_4, and C_2H_2 gas compositions. Based on equations (1), (2), and (3), the following is the calculation of each molecule percentages using the Duval Triangle method:

- % CH_4 = [CH_4 / (CH_4 + C_2H_4 + C_2H_2)] × 100% = [245 / (245 + 18 + 0.2)] × 100% = 93.1%
- % C_2H_4 = [C_2H_4 / (CH_4 + C_2H_4 + C_2H_2)] × 100% = [18 / (245 + 18 + 0.2)] × 100% = 6.8%
- % C_2H_2 = [C_2H_2 / (CH_4 + C_2H_4 + C_2H_2)] × 100% = [0.2 / (245 + 18 + 0.2)] × 100% = 0.1%

The interpretation of the Duval Triangle based on the calculation of the percentages above can be seen in Figure 5. Using the Duval Triangle as shown in Figure 8, the interpretation result indicates a T1 condition, where the thermal fault occurs at a temperature of less than 300 °C.

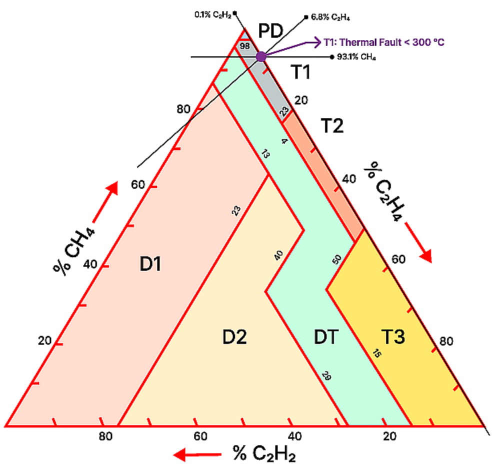

Figure 5. Interpretation Result of Duval Triangle Method

4.5 Comparative Analysis of DGA Interpretation Methods

After interpreting the results of DGA test data processing, below is a comparative analysis of the Rogers Ratio method to determine the outline of the disturbance interpretation.

Table 9. Comparison Results of Rogers Ratio Interpretation on Power Transformers

TDCG	Rogers Ratio (Before Modification)	Rogers Ratio (After Modification)	Duval Triangle
Condition 2	Undetermined	Case 5 (Thermal Fault Between 150 °C – 200 °C)	T1 (Thermal Fault < 300 °C)

Based on the results, the Rogers Ratio method before the modification cannot diagnose interference, while the modified method is able to diagnose the disturbance that occurs in the internal transformer, i.e. Case 5 or thermal fault with temperatures between 150 °C – 200 °C. Compared to the use of the more familiar Duval Triangle method, it turns out that the interpretation results are in, which is T1 or thermal faults with temperatures below 300 °C. Therefore, the Modified Roger Ratio method is not only able to define the disturbance but is also in line and more accurate than the conventional Duval Triangle method.

5. Conclusion

Power transformers are one of the most important and expensive components in the power system. A failure in transformer operation requires expensive repair costs and long downtime to carry out the repair. Therefore, it is beneficial for transformer operators to find signs of failures before the actual failure happens. The DGA method is used to diagnose the types of failures that may occur in power transformers during operation. Conventional methods for DGA diagnosis such as TDCG, Rogers Ratio, and Duval Triangle, have different drawbacks for diagnosing the occurrence of faults in transformers. This research has explored the advantages and effectiveness of the modified Rogers Ratio method in diagnosing disturbances in power transformers, and determination of the transformer's conditions based on the DGA test results.

Based on the results of the DGA analysis using TDCG method, the most dominant gas that appears in the GSUT #1 11/20 kV Transformer of the Manokwari GEPP is Ethane gas (C_2H_6). This indicates that there has been a thermal overload in the internal transformer, but this TDCG method is only able to diagnose disturbances with certain conditions according to the standard, without classifying the disturbance that occurred. The Rogers Ratio method before modification has not been able to provide accurate interpretation or cannot diagnose the disturbance that occurs due to limitations in the interpretation method. On the other hand, the Modified Rogers Ratio method can provide interpretation or diagnosis of the disturbance that occurs in the internal transformer, namely thermal faults at temperatures between 150 °C and 200 °C. When compared to the conventional Duval Triangle method, the interpreted result shows that the fault occurs at a temperature less than 300 °C. Therefore, the result based on the Modified Roger Ratio method is in line and more accurate than the result of the conventional Duval Triangle method.

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