

An Investigation of Insulating Paper Effect on Gas Presence and Aging on Mineral Oil Transformer

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Abstract— A transformer is an essential component in a generator, electrical equipment that works non-stop to support electricity needs. There has been a lot of thermal and electrical activity that the presence of an oil-paper insulator can suppress. The insulating ability can decrease and lead the failure due to the aging of the insulator by heating, moisture, and impurities. The aging of the paper was unavoidable, which caused the cellulose bond to break and form dissolved gases with oil, such as Carbon monoxide, Carbon dioxide, Methane, Acetylene, Ethylene, and Ethane. So, conventional dissolved gas analysis (DGA) was used to investigate further. The use of paper insulation with a certain amount affects the electrical strength of the insulator. A breakdown test on AC voltage is carried out for the following investigation. The result showed that the percentage of paper had an optimum number to get high insulator strength. By heating mineral oil for 250 hours and 500 hours, carbon monoxide and carbon dioxide are released in the different results as the DGA test. It can be concluded that cellulose paper has affected mineral oil's dissolved gas and insulator strength.

Keywords— dissolved gas, mineral oil, paper insulator, strength

I. INTRODUCTION

The transformer is an essential piece of equipment in the electrical system. As in a distribution system, transformers can step up and down as needed and with an insulator to protect systems from various failure types. The insulator used in transformers is usually a combination of oil and paper. The age of the transformer depends on the decomposition that occurs in the fault insulator [1]. A fault in the transformer can result in a functional failure of the transformer. Failure of the transformer is hazardous because it can cause an explosion and fire. The cause of failure itself is due to the influence of external and internal factors. External factors include lightning, switching transients, short circuits and other events. While internal elements can be caused by a decrease in the insulator, overheating, oxygen, moisture, contamination from oil, breakdown conditions, partial discharge and damage during assembly. Failure can also result from paper aging [2].

One of the causes of failure that occurs is partial discharge. Partial discharge is a partial local electric charge between the two conductors of the insulator, which can reduce the workability and life of the transformer. So,

the electronic equipment must be maintained and operated properly [3]. Breakdown voltage is one of the parameters used to design a transformer. It depends on the impurity of the insulator that can be tested [4]. The breakdown test has been utilized IEC 60156 standard on AC voltage by applying spherically or spherical electrode, the distance of electrodes has been arranged in $2,5 \pm 0,05$ millimeters [5, 6].

Paper insulation is formed from cellulose fibers bonded by hydrogen bonds. Aging that occurs in the paper was reasoned by temperature, humidity, and paper coatings which increase the oxygen concentration. The degradation of the paper itself is divided into three factors, temperature, oxidation, and hydrolysis [7]. It was developed to determine the types of faults in transformers by taking oil samples. So far, cellulose paper has been used in combination with oil. This paper was degraded due to heating at excessive temperatures and electrical discharge, which caused the paper content to decompose into certain gases in the oil [8].

The research explained that insulating strength had decreased due to the increase in the paper thickness of insulation because it was associated with an increased concentration of impurities [9]. Dissolved gas analysis (DGA) has been used several times to check equipment in good condition, observe the operational state of transformers, and prevent possible failures. When there are a temperature or electrical failure, the CH and CC bonds of mineral oil will decompose into several new molecules, such as Hydrogen (H_2), Carbon monoxide (CO), Carbon dioxide (CO_2), Methane (CH_4), Acetylene (C_2H_2), Ethylene (C_2H_4) and Ethane (C_2H_6) [10, 11, 12].

Several conventional methods used in the dissolved gas analysis are the Dornenburg ratio method, Rogers ratio method, IEC 60599 method, key gas method, Duval triangle method, Mansour method, and Duval method. The results of a study have been indicated that the Rogers ratio method and the Dornenburg method can be used to determine the health condition of isolation [13, 14].

The current research focused on the presence of cellulose paper, which affected the amount of gas produced during electrical discharge. The appearance of this gas was further enhanced by the addition of cellulose in the discharge cell. So that a specific volume of paper insulation installed was a factor in increasing gas in a state of electrical

stress. Another cause of the appearance of gas was aging that occurred in the oil and contamination of the cellulose paper mixed in the oil. By investigating the heated oil's gas content for several hours, a DGA test was carried out by comparing several gas concentrations before and after the electrical discharge [15].

Therefore, in this study, further investigations were carried out with DGA on insulators that had been conditioned to partial discharge so that the differences between standard insulators could be seen. In addition, the characteristics of the insulator could be investigated by testing the breakdown voltage. The purpose of this research was to examine the effect of paper-oil insulation that has been subjected to thermal and electrical conditions by showing results of DGA analysis and the strength of the insulator.

This paper is divided into five sections, and section II discusses the characteristics of the insulator and the data analysis method used. Section III will show the test set, including the steps of testing and data collection. Section IV describes the results of the experiments, including gas content and insulator strength tests. Finally, the conclusions will be presented in section V.

II. METHODS

This section there can be discussed about the method used in this research. The first subsection will be carried out by examining paper insulation and the material used in the past study. Then there are Dissolved Gas Analysis (DGA) for determining the types of faults, including a discussion about methods used for DGA, such as TDCG, key gas, Roger Ratio, and Duval Triangle.

A. Paper and Oil Insulation

Paper insulation is made from cellulose fibers derived from plants which are the source of cellulose. Cellulose fibers consist of cellulose molecular bonds of different lengths bonded by hydrogen bonds. The aging process on paper has been influenced by temperature and humidity levels, and the paper layer has a high oxygen concentration. By heating cellulose at a temperature of 200 °C, glycosidic bonds are opened due to oxidation and increased humidity [2].

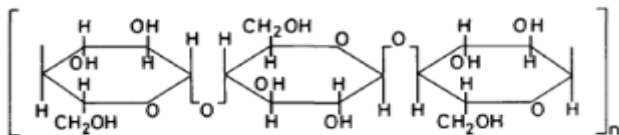


Fig. 1. Cellulose Structure

Mineral oil has been widely used in power transformers and other high-voltage equipment. The impurities in the oil are gradually mixed with metal particles when transferring the oil into the transformer, paper insulation carrying cellulose particles, and long-term use. 90% of impurities are caused by cellulose particles, which increase the bad insulator risk, such as failure [16].

The phenomenon of gas bubbles in oil/paper with the influence of temperature has occurred by heating above temperature 120°C as a result of the evaporation process that caused humidity. With a temperature of more than 160°C, it has reduced the quality of the cellulose. The degradation of solid insulators contributes to the appearance of gases due to the decomposition of the product. The effect of cellulose on the occurrence of gas in mineral oil (such as ASTM D 6180) has been investigated with different proportions of cellulose in aged oil. Cellulose plays a role in forming several gases and moisture in the oil under discharge conditions. The stability evaluation under electrical discharge can change the color of the oil [15].

The appearance of gas bubbles triggers a partial discharge and a breakdown decrease. Temperature, electrical stress, and aging on gas in oil are reported to have several effects. It has been reported in several studies that electrical stress can cause an increase in dissolved decay products, water content, and total acid. The DGA results for paper insulation show that the discharge will produce carbon monoxide and carbon dioxide.

Failures in transformers are triggered by several conditions such as lightning, switching transients, short circuits, and other conditions. Decreases in the insulation are proportional to the transformer age, which is getting older, so it is easy to fail [10]. The proportion of paper insulation can also reduce the performance of the insulator and lead to failure [11].

B. Dissolved Gas Analysis (DGA)

DGA (Dissolved Gas Analysis) is an analysis that uses a method to observe the dissolved gas in the transformer oil and draw conclusions on the prediction of errors. Methods used in DGA analysis are TDCG (Total Dissolved Combustible Gas), key gas, Rogers Ratio, Duval triangle.

TABLE I. DISSOLVED GAS CONCENTRATION

Status	Dissolved Gas Concentration ("µL/L" or ppm)							
	Hydrogen	Methane	Acetylene	Ethylene	Ethane	Carbon monoxide	Carbon dioxide	TDCG
Condition 1	100	120	1	50	65	350	2500	720
Condition 2	101-700	121-400	2-9	51-100	66-100	351-570	2500-4000	721-1920
Condition 3	701-1800	401-1000	10-35	101-200	101-150	571-1400	4001-10000	1921-4630
Condition 4	>1800	>1000	>350	>200	>150	>1400	>10000	>463

TABLE II. ROGERS RATIO METHOD

Case	R2	R1	R5	Fault Analysis
0	<0.1	>0.2 to <1.0	<1.0	Unit normal
1	<0.1	<0.1	<1.0	Low-energy density arcing - PD
2	0.1 to 3.0	0.1 to 1.0	>3.0	Arcing
3	<0.1	>0.1 to 1.0	1.0 to 3.0	Low temperature thermal
4	<0.1	>1.0	1.0 to 3.0	Thermal < 700 °C
5	<0.1	>1.0	>3.0	Thermal < 700 °C

- Condition 1 : The transformer is in good condition. The dissolved gas in the transformer itself
- Condition 2 : Gas level is above normal, errors may occur
- Condition 3 : High-level decomposition
- Condition 4 : Continued decomposition. If the transformer is used continuously, it can cause transformer failure.

TDCG is difficult to perform if the transformer is used in normal conditions because no dissolved gas is recorded. There are four levels to classify the risk of transformers with varying gas levels.

Key gas is a method that depends on the temperature of the type of oil and gas decomposition of cellulose. It can determine the type of error at temperature variations divided into four types of errors [17].

- Overheated oil: This Shows the proportion of ethylene, hydrogen, methane and ethane
- Overheated cellulose: presents a high proportion of carbon monoxide
- Partial discharge: discover methane, ethane, ethylene and high hydrogen
- Arcing in oil: discovers hydrogen, methane, ethylene and acetylene.

Doernenburg ratio is an analytical method that uses the ratio of R1, R2 and R5. First, the gas value obtained is entered in equation (1-3). The ratio calculation can be validated with Table 2 to see the diagnosis.

$$Ratio\ 1\ (R1) = CH_4/H_2 \quad (1)$$

$$Ratio\ 2\ (R2) = C_2H_2/C_2H_4 \quad (2)$$

$$Ratio\ 5\ (R5) = C_2H_4/C_2H_6 \quad (3)$$

Duval triangle 1 and roger ratio are commonly used methods with relatively accurate values. The gas formation can occur at any temperature, and identification can be done by selecting one of the appropriate methods because each has its sensitivity. In the case of heating cellulose or liquid insulator, the gases formed are CO and CO₂. Abnormal conditions in a transformer can be seen if there is the formation of C₂H₂ gas. Besides, the presence of CH₄, C₂H₄ and C₂H₆ can be detected if there is the heating of oil or paper.

Duval triangle 1 uses three kinds of gases that increase energy or temperature in error. The gases are CH₄, C₂H₂ and C₂H₄. This method classifies gases in triangles, as in Figure 3, where each side of the triangle represents a percentage of the three gases. The gas ratio can be calculated like the following formula if each gas is assumed in xyz, C₂H₂ = x; CH₄ = y; C₂H₄ = z("μL/L" or ppm). To categorize errors into PD (partial discharge), D1 (low energy discharge), D2 (high energy discharge), DT (mix of thermal and electrical faults), T1 (thermal fault<300°C), T2(thermal fault 300°C -700°C) and T3 (thermal fault >700°C) limits [18].

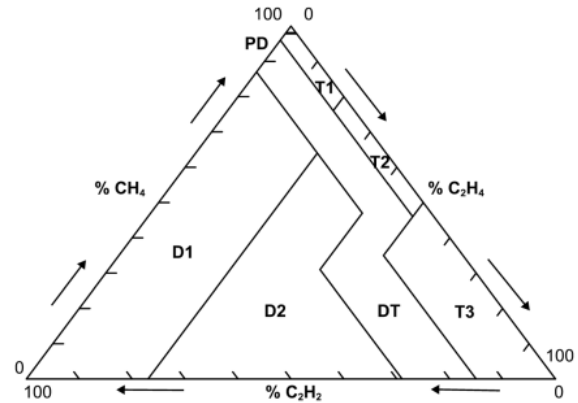


Fig. 2. Duval Triangle 1 Method Boundaries

$$\% C_2H_2 = 100x/(x+y+z) \quad (4)$$

$$\% CH_4 = 100y/(x+y+z) \quad (5)$$

$$\% C_2H_4 = 100z/(x+y+z) \quad (6)$$

Rogers Ratio Method is often used to detect fault by using direct analysis from the obtained value of carbon portion per gas level.

III. EXPERIMENTAL SETUP

This section described the experimental setup from the initial design using paper until a decent sample of the results was obtained, which could be analyzed through a few percent of the paper material in the insulating material mixture. Lastly, the effects were explored through a graph of the strength insulation in voltage per percentage paper.

First, the insulating paper was dried to reduce water contamination, and the oil condition was filtered. For ensuring the paper could be completely dissolved in the oil, the paper-oil sample was heated to a temperature of 60°C with an ultrasonic cleaner. Then the paper-oil sample was heated in a vacuum oven at 115°C for 250 hours and 500

hours to simulate the presence of thermal aging. The test steps are presented in Figure 3.

After heating was done, the sample was tested with breakdown to see the characteristics of the insulator. The sample was reheated in a vacuum oven for ten days. The temperature was increased and decreased every day from 60°C to 100°C. A partial discharge was tested to see the effect of the sample, then a breakdown test was carried out again, and the DGA results were taken.

initial insulating paper material testing process would be conducted.

After the insulating paper material testing process was decent enough, the temperature setting and insulating paper material testing process would be performed for better comparison.

Lastly, the result analysis, reporting process, conclusions, and suggestions would be done after all steps were done and the best approach for the research goals.

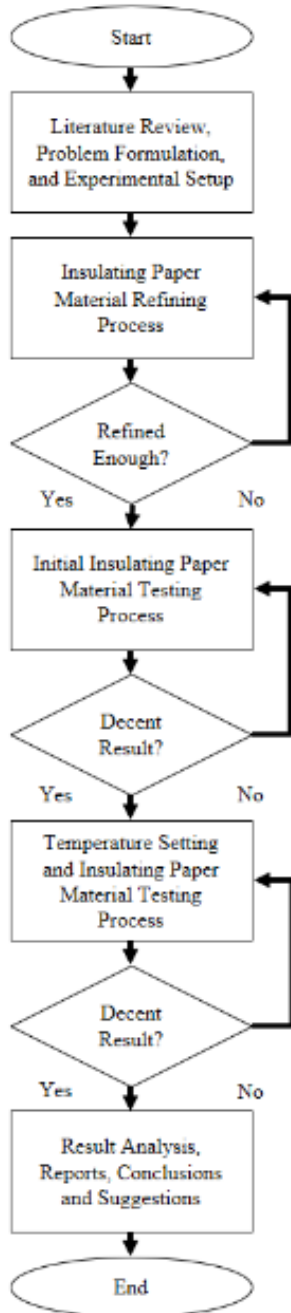


Fig. 3. Experimental Flowchart

The literature review, problem formulation, and experimental setup were set from the first round of the experimental flowchart. Then, the insulating paper material refining is processed for a better approach in terms of results validity. If the insulating paper was refined enough, the

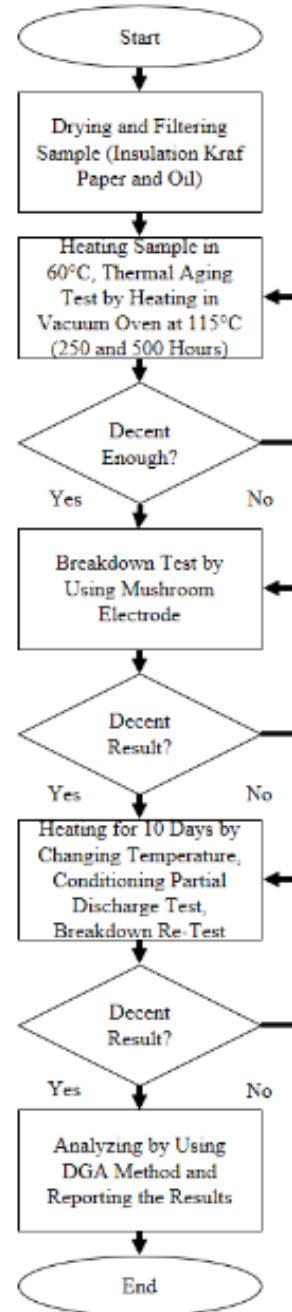


Fig. 4. Methodology Flowchart

From figure 4, the methodology flowchart has been explained, and there would be conducted a drying and filtering sample process. Using insulation kraft paper and oil, then heating sample in 60°C, and then Thermal Aging Test

by Heating in Vacuum Oven at 115°C (250 and 500 hours) would be seen decent enough or not as a result.

A breakdown test using a spherical electrode would be performed after the decent experimental results. Then, the heating for ten days by variable temperature and conditioning partial discharge test was done for better comparison. After that, the breakdown re-test was performed on the renewal material. The oil used has a different lifespan of 0, 250 and 500 hours, and the oil type is shell diode B. The paper used is kraft paper. Cellulose paper is added to the oil in a ratio of 0%, 10% and 30% of the mass of oil. The paper insulator used is cut into small pieces.

Lastly, the analysis by using DGA Method for reporting and collecting results was performed at the end of the research.

IV. EXPERIMENTAL RESULTS

Paper insulators that have been immersed in mineral oil that has been removed with an ultrasonic cleaner can produce a cellulose concentration of 41.51%. To more clearly see the effect of cellulose paper in oil is described in the following results.

A. Effect of Paper on Insulator Strength

Paper insulators are added to mineral oil samples with different percentages and heating times. Changes that can be seen from the addition of paper with different proportions and times can be seen in Figure 5. The breakdown voltage is increasing when the percentage of paper increase approximately 10 to 30 percent (and have a high probability to decrease after that) due to the enhancement of the paper characteristics.

The breakdown voltage test is carried out on the test medium with spherical electrodes with an AC voltage source of 220 volts. The purpose of this test is to determine the characteristics of how much the insulator used can withstand high voltages with results as shown in Figure 5. Breakdown tests on paper percentages of 0%, 10%, and 30% resulted in different stress strengths. The difference is seen in an increase in the voltage characteristics of 0% and 10% paper, and on 30% paper, the voltage decreases, the breakdown test for 250 hours and 500 hours of heating has the same characteristics. This result shows that the use of paper in oil insulators has a special optimal value. In the results of this study, a percentage of 10% paper can produce good paper characteristics because the oxidation process that occurs and humidity is not too high, even with the addition of paper can increase the strength of the insulator.

The longer the paper heated in the oven decreased in strength. Due to the more humid conditions during heating, it could increase the humidity and the concentration of air bubbles in the oil. Therefore the strength of the paper decreased, as depicted in Figure 6.

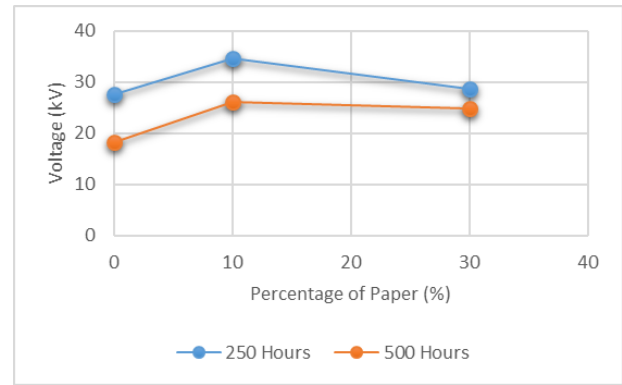


Fig. 5. Breakdown Test After Long Heated

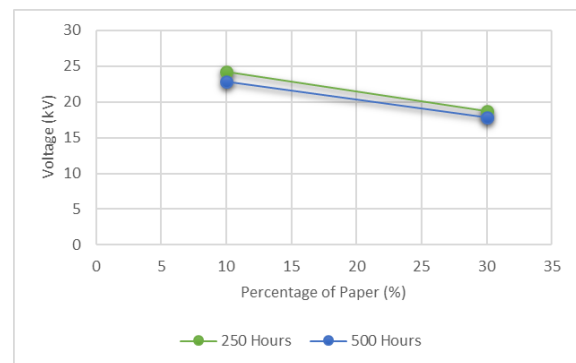


Fig. 6. Strength of Insulation After Partial Discharge

B. Effect of Paper on Dissolved Gas

DGA analysis was carried out with various paper variables to see the effect of adding paper on the oil insulator. Dissolved gases could be detected in more significant numbers after electrical activation, such as partial discharge and breakdown tests were given.

Partial discharge conditioning in oil was more challenging to observe because of the influence of contamination mixed in the oil, and the nature of the oil was more stable than air media. So that for the observation process in this condition, the electrodes were given a longer distance, the appearance of partial discharges could be observed higher and more. The gas formed before this conditioning can be seen in Figure 8.

From Figure 7, it is illustrated that in all samples with variations in the percentage of paper and heating time, it shows that the dominating gases are carbon dioxide and carbon monoxide. Based on the DGA analysis using the key gas method with a long heating process, carbon dioxide and carbon monoxide indicated overheated cellulose [4]. From the results of the DGA test analysis, it can be seen that cellulose decomposed from kraft paper can affect the formation of gas in mineral oil. The presence of carbon dioxide gas proves that carbon monoxide was observed. The gas concentration was getting higher with the increasing percentage of gas and the longer the heating process related to the oxidation process. With this kind of analysis, further observations are needed.

The difference was observed with the conditioning after the partial discharge test, and the test results showed the

formation of ethylene and acetylene gas. This result can indicate that the insulator is in bad condition and needs further testing, as shown in Figure 9. Analytical methods such as TDCG and Dornenburg key gas method are not appropriate because the DGA test kit has optimal specifications for only a few methods. The TDCG and Dornenburg key gas show that the insulator is still average or good. For further results, analyzed using the Rogers key method, the analysis results show that the concentrations of gases are entered in formulas 1-3 and matched with the Rogers key table in Table 2. The analysis shows that the insulator in case 1 is indicated by low energy density arcing – partial discharges. It is according to the conditioning carried out by the partial discharge test. The gas concentration is getting higher linearly with the higher percentage of paper and heating time.

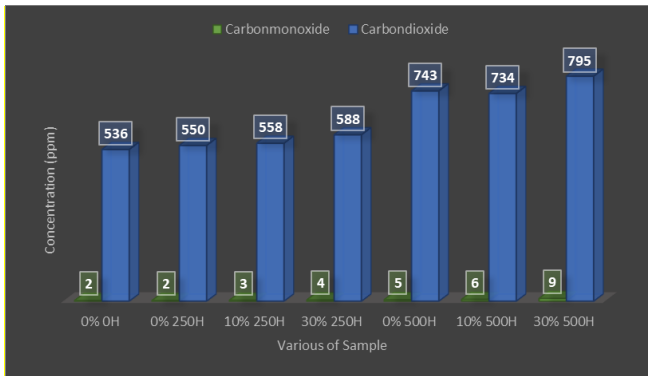


Fig. 7. Presence of Gas at Various Sample

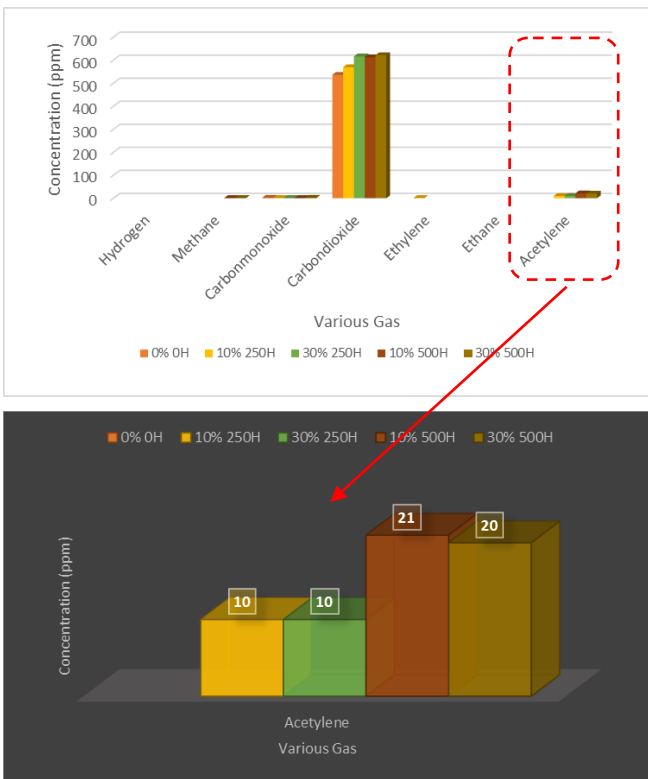


Fig. 8. Presence of Gas After Partial Discharge and Acetylene Parts

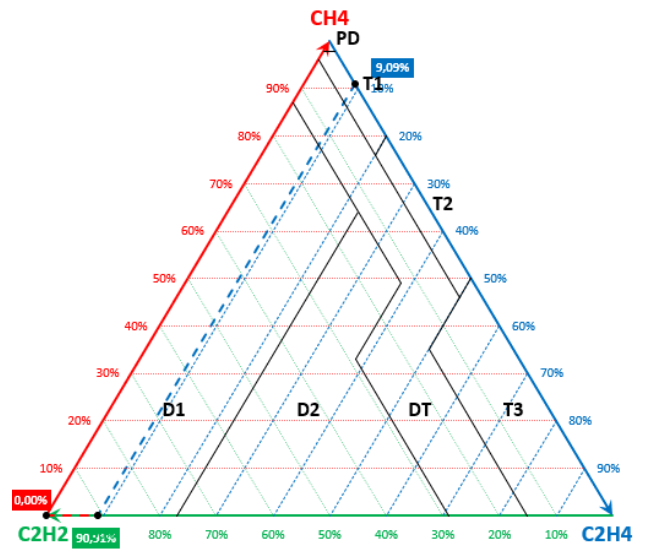


Fig. 9. Duval Method Analysis of 10% 250 Hours Sample

The following analysis method is to use a Duval triangle. From the concentration results in ppm Figure 8, the percentage is calculated using the formula 4-6. Then it is included in the Duval triangle in Figure 3. One of the results presented in Figure 9, the analysis results for 10% 250 hours show that with this method, the insulator is indicated in the D1 condition - low energy discharge (sparking). For the 30% sample 250 hours, 10% 500 hours, and 30% 500 hours, the results show the D1 condition, while for the 0% in 0 hours sample, it does not produce results because the sample is not heated and does not get a partial discharge condition (meaning normal conditions). Using the methods has function and purpose, so it cannot be used for all test samples.

V. CONCLUSION

In this research, the effect of paper on gas generation and strength of transformer mineral oil has been investigated. The result of increasing the percentage of paper (0%, 10%, and 30%) gives different effects in different heating. Diagnosis is made by observing the strength of the breakdown voltage. Observing the strong ability of the insulator and analysis with DGA has been reported above. Based on this research, the addition of cellulose paper to mineral oil has an optimal value so that the results of the breakdown strength are higher. The effect of adding paper is seen with the appearance of CO and CO₂ gases. The result of analysis with DGA can only be done with the gas key, Rogers key, and the Duval triangle method because the DGA analysis method has its function and suitability. The increase in cellulose paper in O₂ and N₂ can show a significant difference for further research. This contribution opens up greater equipment use and more organized conditioning during testing.

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