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Analysis of the Insulation Quality of 1000 kVA Distribution Transformer Oil Due to Aging at PT. Bambang Djaja Surabaya

Reza Sarwo Widagdo [a,1], Puji Slamet [b,2], Aris Heri Andriawan [c,3], and Bima Bayu Santoso [d,4]
[a, b, c, d] Department of Electrical Engineering, Universitas 17 Agustus 1945 Surabaya, Indonesia
Email coresponden author: rezaswidagdo@untag-sby.ac.id

Abstrak

Penelitian ini mengkaji dampak penuaan pada kualitas isolasi minyak transformator distribusi 1000 kVA di PT. Bambang Djaja Surabaya. Uji Breakdown Voltage (BDV) dilakukan dalam tiga tahap, yang menunjukkan penurunan signifikan pada nilai BDV di setiap uji. Uji pertama menunjukkan nilai BDV berkisar antara 62,7 kV hingga 74,6 kV (rata-rata 68,7 kV), yang mengindikasikan kualitas isolasi yang baik. Pada uji kedua, nilai BDV sedikit menurun, berkisar antara 53,1 kV hingga 78,4 kV (rata-rata 66,3 kV). Uji ketiga menunjukkan penurunan yang lebih besar, dengan nilai berkisar antara 42 kV hingga 69,8 kV (rata-rata 57,22 kV), yang menunjukkan kemungkinan degradasi isolasi. Penurunan ini mungkin disebabkan oleh beberapa uji yang dilakukan atau faktor eksternal seperti suhu dan kelembaban. Analisis distribusi Weibull digunakan untuk mengevaluasi keandalan data BDV, dengan parameter bentuk (β) yang menurun dari 17,32 untuk BDV 1 menjadi 6,447 untuk BDV 3, yang mengindikasikan kehilangan keandalan. Analisis gas juga dilakukan, mengidentifikasi senyawa kunci seperti Metana (CH4), Etilena (C2H4), dan Asetilena (C2H2), yang merupakan indikator degradasi minyak dan kerusakan listrik. Tingkat Total Dissolved Combustible Gases (TDCG) tetap dalam batas yang dapat diterima, yang menunjukkan bahwa transformator beroperasi dengan normal. Namun, rasio gas menunjukkan kemungkinan adanya masalah internal seperti pelepasan sebagian (partial discharge) dan pemanasan berlebih. Temuan ini menekankan pentingnya pemantauan berkelanjutan dan pemeliharaan prediktif untuk memastikan operasi yang andal dan umur panjang transformator.

Abstract

This study examines the impact of aging on the insulation quality of 1000 kVA distribution transformer oil at PT. Bambang Djaja Surabaya. Breakdown Voltage (BDV) tests were conducted over three stages, showing a significant decline in BDV values with each test. The first test exhibited BDV values ranging from 62.7 kV to 74.6 kV (average 68.7 kV), indicating good insulation. In the second test, BDV values slightly decreased, ranging from 53.1 kV to 78.4

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kV (average 66.3 kV). The third test revealed a more substantial drop, with values ranging from 42 kV to 69.8 kV (average 57.22 kV), indicating possible insulation degradation. This reduction may result from multiple tests or external factors, such as temperature and humidity. Weibull distribution analysis was used to evaluate the reliability of the BDV data, with the shape parameter (β) decreasing from 17.32 for BDV 1 to 6.447 for BDV 3, indicating a loss of reliability. Gas analysis was also performed, identifying key compounds such as Methane (CH4), Ethylene (C2H4), and Acetylene (C2H2), which are indicators of oil degradation and electrical faults. Total Dissolved Combustible Gases (TDCG) levels remained within acceptable limits, suggesting that the transformer was operating normally. However, gas ratios indicated the possibility of internal issues like partial discharge and overheating. These findings underline the importance of continuous monitoring and predictive maintenance to ensure the reliable operation and longevity of the transformer.

Introduction

A transformer is an energy conversion device that functions to change alternating current (AC) or an AC voltage level to another voltage level. Transformers are also used to step down the voltage from equipment to lower distribution voltages or to voltages required by power generation facilities (Widagdo *et al.*, 2024). Transformers are reliable devices and can provide service for a long time if maintained regularly (Widagdo *et al.*, 2024) The degradation of electrical equipment performance is a natural process that begins when the equipment is first installed. If this degradation is not addressed promptly, it can lead to failures and malfunctions. To maintain transformer performance, one method is by maintaining the insulation medium, whether liquid or solid, using various diagnostic methods that adhere to recommended standards (Widagdo *et al.*, 2023). There are four maintenance guidelines for assessing transformer condition: in-service inspection, in-service measurement, shutdown testing, and treatment (Widagdo *et al.*, 2023). One test for transformer insulation oil involves Dissolved Gas Analysis (DGA) (Ali *et al.*, 2023). This test is performed to analyze the condition of the insulation oil by taking oil samples from the transformer unit to identify the types of gases dissolved in the transformer oil (Piotrowski *et al.*, 2020). Several studies have been conducted, including analysis of transformer aging factors (Vita *et al.*, 2023), failure event analysis (Badawi *et al.*, 2022), and the capability of static winding resistance tests as an indicator of condition, which is performed by comparing two different conditions: before and after maintenance (Lin *et al.*, 2020). A study on methods and procedures for evaluating the Total Dissolved Combustible Gas (TDCG) method has been applied to recommend maintenance types (Irungu & Akumu, 2020).

Various studies have been conducted on the quality of transformer oil insulation to understand the factors affecting its performance. Research shows that thermal and electrical stress are the primary causes of transformer oil degradation, producing gas compounds such as carbon monoxide (CO) and carbon dioxide (CO_2). Key parameters like breakdown voltage, moisture content, and furan concentration are used to evaluate oil condition (Febrina, 2022). Dissolved Gas Analysis (DGA) is an effective diagnostic method for detecting degradation gases such as hydrogen (H_2), acetylene (C_2H_2), and methane (CH_4), enabling early detection of potential failures before major damage occurs (Bustamante *et al.*, 2019). Additionally, studies reveal that high moisture content in transformer oil significantly reduces its dielectric performance and increases the risk of insulation failure (Rao *et al.*, 2019). As an alternative to mineral oil, vegetable oil has been tested and proven to have high biodegradability, excellent cooling capabilities, and lower oxidation resistance (Tlhabologo *et al.*, 2021). Other research highlights the correlation between oil color and transformer aging, where darker oil indicates higher oxidation levels. Parameters such as acid number and sludge are also used to complement these analyses. These studies provide valuable insights for improving the reliability of transformers through maintenance of insulating oil (Negara *et al.*, 2018).

The insulating oil in distribution transformers gradually degrades over time, potentially compromising both the performance and reliability of electrical power systems. While numerous studies have investigated oil degradation, most have been limited to laboratory-based simulations or focused on large-capacity transformers, leaving a research gap in understanding the real-world aging behavior of insulating oil in medium-capacity units, particularly 1000 kVA transformers. Moreover, there is a scarcity of studies conducted under actual operational conditions, especially within industrial environments in Indonesia. As a result, there is a critical need for field-based research to assess the impact of environmental factors and operational stresses on the aging process of insulating oil.

This study seeks to bridge that gap by evaluating the aging characteristics of transformer oil using real operational data obtained from PT. Bambang Djaja Surabaya. The novelty of this research lies in its practical, age-based analysis and its emphasis on key degradation indicators such as Breakdown Voltage and dissolved gas content, which offer valuable insights for implementing predictive maintenance strategies in power distribution systems. The findings from this study are expected to support the development of more effective asset management practices. Furthermore, they may contribute to enhancing the operational lifespan and safety of distribution transformers.

Method

This section describes the research method used to analyze the insulation quality of 1000 kVA distribution transformer oil due to aging at PT. Bambang Djaja Surabaya. The study is conducted using an experimental approach involving chemical and electrical testing of transformer oil samples at various stages of service life. The main parameters analyzed include Breakdown Voltage (BDV) and Dissolved Gas Analysis (DGA) Test. The testing process refers to relevant international standards, such as IEC and ASTM, to ensure the accuracy and validity of the data obtained. This method aims to provide a comprehensive overview of the effects of aging on the insulation quality of transformer oil, thus supporting maintenance efforts and improving the performance of transformers in the field.

Breakdown Voltage (BDV) Test

Insulation failure can result from aging, reduced dielectric strength, overvoltage, and contamination. When voltage is applied, internal forces counteract stress, but material bond breakage can degrade insulation. Contaminants like carbon or moisture lower breakdown voltage, while high currents can raise conductor temperature, potentially igniting insulating oil. Partial discharge in the oil also weakens insulation. Differences in breakdown strength between liquid and solid materials can cause failure in the weakest material, leading to partial discharge. These discharges cause gradual deterioration because (Andriyanti *et al.*, 2022):

a. Disintegration of the solid dielectric due to bombardment by the electrons and ions produced.
b. Chemical actions on the dielectric due to gas ionization.
c. High temperatures in the discharge region.

Electrochemical deterioration occurs when ions released by electric current at the electrode interact with the surrounding medium, potentially causing structural or chemical damage. The severity of this deterioration depends on the type of ions involved and the nature of the ionization reactions. In this study, the test electrode is a hemispherical brass configuration with diameters ranging from 0.1 mm to 0.5 mm, designed in accordance with the IEC 156 standard, which specifies a 35 mm electrode spacing. The test chamber is constructed from acrylic plastic and has external dimensions of 100 mm × 100 mm × 80 mm.

It is designed to securely hold the test electrodes and to contain the insulating liquid during breakdown voltage measurements. All measurements were conducted under controlled laboratory conditions to ensure consistency and reliability of the results.

Table 1
Standart of Breakdown Voltage (Cahya *et al.*, 2019)

Test Type	Voltage	Distance	Standart
Breakdown Voltage Test	≥ 170	≥ 50 kV / 2,5 mm	IEC 156
	70 – 170	≥ 40 kV / 2,5 mm	
	≤ 170	≥ 30 kV / 2,5 mm	

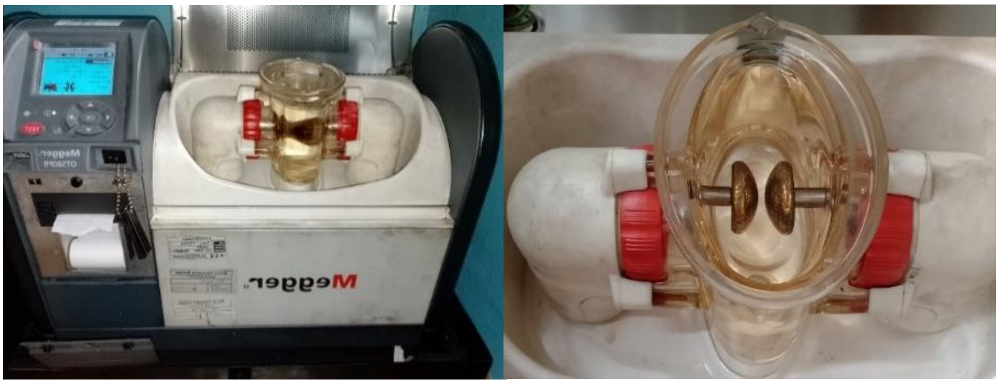

Figure 1. Breakdown Voltage (BDV) Tester

Dissolved Gas Analysis (DGA)

Dissolved Gas Analysis (DGA) is a process used to measure the concentration of hydrocarbon gases formed due to abnormalities in insulating oil, using a DGA testing device. From the detected gas composition, the impacts of abnormalities in the transformer can be predicted, such as overheating, arcing, or corona. In DGA testing with chromatography schemes, nine types of gases are detected, including Hydrogen, Methane, Carbon Monoxide, Carbon Dioxide, Ethylene, Ethane, Acetylene, Nitrogen, and Total Dissolved Combustible Gas (TDCG). After obtaining the DGA test results, the data is adjusted and analyzed based on the concentration of each detected gas using the Dissolved Gas Analysis (DGA) Method.

Figure 2. Gas *Cromathography*

Dissolved Gas Analysis (DGA) method is a testing technique used to determine the amount of combustible gases formed due to abnormalities detected in the insulating oil of power transformers. The gases commonly analyzed include Hydrogen (H_2), Acetylene (C_2H_2), Methane (CH_4), Ethylene (C_2H_4), Ethane (C_2H_6), and Carbon Monoxide (CO). DGA consists of four main methods, which are:

1. TDCG (Total Dissolved Combustible Gas): Measures the total amount of combustible gases dissolved in the oil.
2. Rogers Ratio: Compares the concentration ratio of two specific gases to assess the transformer condition.

This DGA method aids in analyzing abnormalities and disturbances that can affect transformer performance, such as Overheating, Partial Discharge, Arcing, Hot Metal, Cellulose Insulation Degradation, and Corona. The Institute of Electrical and Electronics Engineers (IEEE) Standards Std C57-104-2008 and Std C57-104-2019 provide guidelines for the implementation and interpretation of DGA results (Muhammad *et al.*, 2023).

Table 2

Transformer Insulating Oil Condition based on TDCG (Subekti *et al.*, 2023)

No.	Gas Test Parameter	IEEE Std C57.104-2008			
		Condition 1	Condition 2	Condition 3	Condition 4
1.	Hidrogen (H_2)	100	101-700	701-1800	>1800
2.	Methane (CH_4)	120	121-400	401-1000	>1000
3.	Acetylene (C_2H_2)	1	>2-9	>10-35	>35
4.	Ethylene (C_2H_4)	50	51-100	101-200	>200
5.	Ethane (C_2H_6)	65	66-100	101-150	>150
6.	Carbon Monoxide (CO)	350	351-570	570-1400	>1400

7.	Carbon Dioxide (CO_2)*	2500	2500-4000	4001-10000	>10000
TDCG*)		720	721-1920	1921-4630	>4630
Condition 1 = Normal gas content amount					
Condition 2 = Abnormal gas content					
Condition 3 = The amount of gas content is very abnormal					
Condition 4 = The amount of gas content is very abnormal					

Based on Table 2, the context of the TDCG (Transformer Differential Gas Chromatography) test, the levels described above are used to assess the health and operational status of a transformer. The TDCG test measures the concentration of gases produced inside a transformer, which can indicate potential issues. Condition 1, where TDCG is below a certain threshold, suggests that the transformer is functioning normally, with no signs of distress. If any gas concentration exceeds this threshold, immediate investigation is required to detect early signs of a problem. Condition 2 signals that the concentration of combustible gases has exceeded normal levels, which could indicate the onset of a fault. In this case, it's crucial to observe trends in gas levels, as the transformer may be experiencing stress.

Condition 3 indicates high-level decomposition within the transformer, signaling a more serious issue. If any gas readings exceed this level, it's vital to conduct a thorough investigation and track trends to identify the underlying cause of the decomposition. Condition 4, where TDCG values exceed the highest threshold, points to severe deterioration and puts the transformer at risk of catastrophic failure. Continuing operations without intervention could result in irreversible damage, making immediate action necessary to prevent further degradation. The TDCG test, therefore, serves as a crucial diagnostic tool to monitor the condition of transformers and prevent potential failures by identifying gas levels indicative of various operational problems.

Table 3
Rogers Ratio Methods (Furqaranda et al., 2022)

Rogers Ratio Methods				
Case	**C_2H_2 / C_2H_4**	**CH_4 / H_2**	**C_2H_4 / C_2H_6**	**Fault Diagnosis**
0	< 0.1	0.1 to 1.0	< 0.1	Unit normal
1	< 0.1	< 0.1	< 0.1	Low energy density arcing-PD
2	0.1 to 3.0	0.1 to 1.0	> 3.0	Arcing-High-energy discharge
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	Thermal > 700°C

The Rogers Ratio method is a gas content analysis technique used to identify the causes of faults in transformer insulation oil. This method involves calculating the ratios of various gases present in the transformer oil, such as C_2H_2/C_2H_4, CH_4/H_2, and C_2H_4/C_2H_6. These gases can form as a result of faults or damage to the transformer, such as overheating or arcing. Once the gas ratios are calculated, the results can be compared with the standards provided in Table 3 of IEEE Std C57.104-2019. This standard serves as a guideline for analyzing the transformer's condition based on the gas analysis results, helping to determine whether a fault exists and what type of fault it might be.

Results and Discussion

In this study, an analysis was conducted on the insulation quality of 1000 kVA distribution transformer oil operating at PT. Bambang Djaja Surabaya to understand the effects of aging on its insulating properties. The test results indicate a deterioration in the transformer oil quality as the operational age increases, evidenced by changes in dielectric strength observed in the oil samples. The subsequent discussion will explore the factors contributing to this decline in quality, as well as its long-term impact on transformer performance. Mitigation strategies and maintenance recommendations will also be proposed based on these findings.

Breakdown Voltage (BDV) Test Analysis

The testing using the BDV (Breakdown Voltage) method is conducted to assess the quality of insulating oil and to determine its ability to withstand voltage stress. Clear and dry oil will exhibit a high breakdown voltage value. This test is performed by taking a sample of the oil using a sampling bottle, which is then tested for its quality to achieve the desired results. The breakdown voltage (BDV) test refers to the IEC 60156 testing standard. The transformer oil testing standard using the breakdown voltage method is as shown in Table 4.

Table 4
Breakdown Voltage (BDV) Test Result

1st BDV Testing		2nd BDV Testing		3rd BDV Testing	
Testing Sequence	Breakdown Voltage (kV)	Testing Sequence	Breakdown Voltage (kV)	Testing Sequence	Breakdown Voltage (kV)
1	62,7	1	78,4	1	67,3
2	69,5	2	69,7	2	58,6
3	64,3	3	70,9	3	69,8
4	69,1	4	59,5	4	48,4
5	74,6	5	53,1	5	42

Average	68,7	Average	66,3	Average	57,22

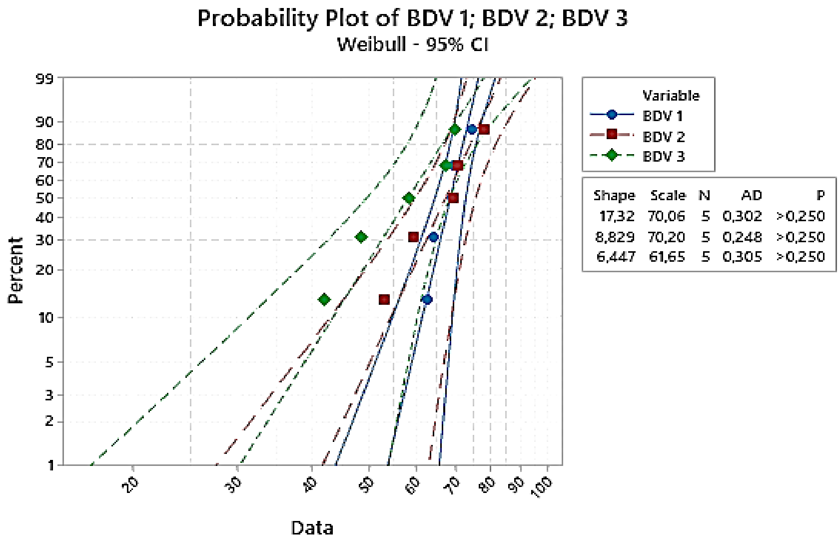

Figure 3. Weibull Probability Plot for BDV Test

The breakdown voltage (BDV) test results in Table 4 show a significant decrease in each successive test. In the first test, the BDV values ranged from 62.7 kV to 74.6 kV, with an average of 68.7 kV, indicating good insulation quality. In the second test, the BDV values slightly decreased, ranging from 53.1 kV to 78.4 kV, with an average of 66.3 kV. However, a more significant drop is observed in the third test, where the BDV values ranged from 42 kV to 69.8 kV, with an average of 57.22 kV. This sharp decline in the third test could be due to insulation degradation after several tests or external factors such as temperature or humidity affecting the results. Overall, the significant drop in BDV suggests possible damage to the insulation or changes in environmental conditions that affect insulation quality.

This analysis includes three data sets (BDV 1, BDV 2, and BDV 3), each of which is characterized by the Weibull parameters shown in Figure 3. The shape parameter (β), which indicates the reliability of the data, is highest for BDV 1 (17.32), followed by BDV 2 (8.829) and BDV 3 (6.447). This suggests that BDV 1 has the most consistent performance. The scale parameter (η), representing the BDV value at 63.2% reliability, is approximately 70 kV for BDV 1 and BDV 2, whereas BDV 3 has a lower value of 61.65 kV, indicating reduced reliability. The goodness-of-fit analysis, based on the Anderson-Darling (AD) statistic and p-values, shows that all datasets fit the Weibull distribution well, with p-values greater than 0.25. This confirms the suitability of the Weibull model for the data. From the probability plot, BDV 1 exhibits the highest reliability, as indicated by the steep slope of its curve (blue line). BDV 3, on the other hand, shows the lowest reliability, with a shallower slope and lower scale value (green line). BDV 2 falls between these two, with moderate reliability (red line).

Dissolved Gas Analysis (DGA) Test Analysis

This section presents the results of Dissolved Gas Analysis (DGA) testing performed on power transformers. Two primary diagnostic methods were utilized: Total Dissolved Combustible Gas (TDCG) and the Rogers Ratio method. The TDCG approach quantifies the overall concentration of dissolved combustible gases in the insulating oil, serving as a general indicator of the transformer's operational condition. In contrast, the Rogers Ratio method analyzes specific ratios between key gases to diagnose the nature of faults, such as overheating, arcing, or thermal degradation. By combining these two diagnostic techniques, a more comprehensive and accurate assessment of transformer health is achieved, enabling early fault detection and supporting the continued reliability of the power system.

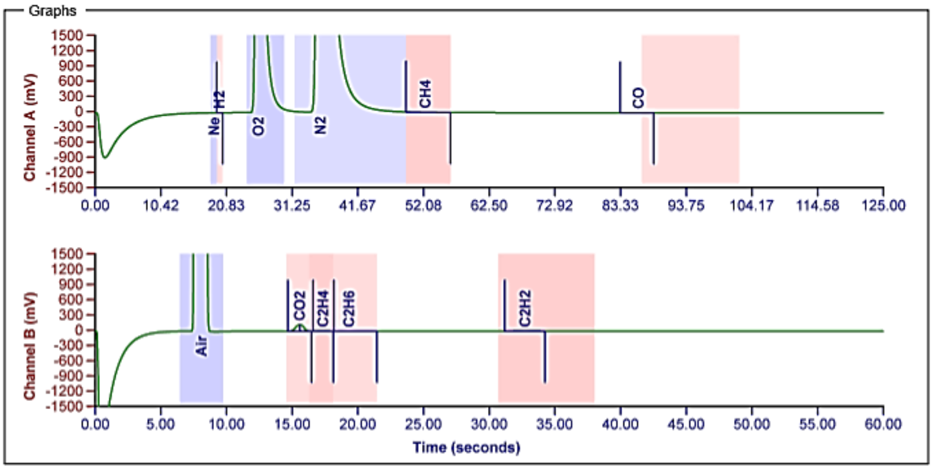

Figure 4. Dissolved Gas Analysis (DGA) Test Result

Based on Figure 4, the graph from Channel A identifies gases such as Neon (Ne), Hydrogen (H_2), Oxygen (O_2), Nitrogen (N_2), Methane (CH_4), and Carbon Monoxide (CO). These gases appear at specific time intervals, reflecting sensor responses to individual gases. The presence of CH_4 (Methane) and CO (Carbon Monoxide) is critical for detecting oil or paper insulation degradation caused by overheating or oxidation. Meanwhile, Channel B detects gases like Air, Carbon Dioxide (CO_2), Ethylene (C_2H_4), Ethane (C_2H_6), and Acetylene (C_2H_2). Gases such as C_2H_4 (Ethylene) and C_2H_2 (Acetylene) are typically associated with high-temperature faults or electrical discharges within the transformer, while CO_2 levels indicate possible paper insulation degradation. Key observations include the detection of Hydrogen (H_2) and Acetylene (C_2H_2), which are primary indicators of electrical faults involving arcing or high-energy discharges. Methane (CH_4) and Ethylene (C_2H_4) suggest oil degradation due to overheating, while Carbon Monoxide (CO) and Carbon Dioxide (CO_2) provide insights into the condition of the paper insulation.

Table 5
Dissolved Gas Analysis (DGA) Test Result Based on TDCG

Dissolved Gas Analysis (DGA) Test Result								
Date	***Hydrogen (H_2)***	***Methane (CH_4)***	***Ethylene (C_2H_4)***	***Ethane (C_2H_6)***	***Acetilene (C_2H_2)***	***Carbon Monoxide (CO)***	***Carbon Dioxide (CO_2)***	**TDGC**
23/03/24	7	110	36	23	0	181	1150	357

Based on the data presented in Table 5, the compound concentrations in the transformer oil indicate that the Total Dissolved Combustible Gases (TDCG) value remains within the acceptable range. According to the IEEE Std C57-104-2008 classification, the TDCG level falls under Category 1, which signifies that the transformer is operating under normal conditions with no immediate risk to performance. While this suggests the unit is functioning reliably, it remains crucial to maintain continuous monitoring of dissolved gas levels. These gases serve as early indicators of potential internal issues, such as thermal stress, arcing, or insulation degradation, which may not be immediately apparent through conventional inspection methods. Routine DGA testing helps track changes in gas composition over time, providing valuable information for predictive maintenance and minimizing the risk of unexpected failures. Furthermore, following the acquisition of DGA test results, additional diagnostic analysis was conducted using gas ratios C_2H_2/C_2H_4, CH_4/H_2, and C_2H_4/C_2H_6 which yielded the following interpretations:

$$R_1 = \frac{C_2H_2}{C_2H_4} = \frac{0}{36} = 0$$

$$R_2 = \frac{CH_4}{H_2} = \frac{110}{7} = 15.7$$

$$R_3 = \frac{C_2H_4}{C_2H_6} = \frac{36}{23} = 1.56$$

From the results, it is known that the fault gas ratio R_1 C_2H_2/C_2H_4 is 0.00 (<0.1), R_2 CH_4/H_2 is 15.7 (>1.0), and C_2H_4/C_2H_6 is 1.56 (<1.0). Referring to Table 3 of the IEEE Standard Std C57.104-2019, the Roger's Ratio corresponds to Case 4. This can lead to corona, partial discharge, and also low and medium thermal disturbances with a thermal temperature <700℃. With the increasing years of transformer use and loading, the amount of compound gases in the oil also tends to increase. One of the gases that has increased is Methane (CH_4), which can be detected from the TDCG method results, which are almost reaching or exceeding the threshold of 1 (110 < 120), indicating the presence of corona, partial discharge, and overheating, possibly caused by high energy discharge during the transformer's energization process. Therefore, when turning off and restarting the transformer, along with maintenance and servicing over time, it is important to pay attention to these conditions.

Conclusion

The results of testing and analysis of transformer oil insulation based on the Breakdown Voltage (BDV) and Dissolved Gas Analysis (DGA) methods show that the insulation quality of the 1000 kVA distribution transformer meets the established standards. Due to the effects of aging, in the Breakdown Voltage test, the condition of the transformer oil after aging still meets the standard as good, although in some tests, the breakdown voltage fluctuates. This is caused by changes in the density of compounds present in the transformer oil.

In the DGA test using the TDCG method, the condition of the transformer oil after aging falls into condition 1 (normal), although there is one compound (CH_4) with a high concentration that is almost exceeding the threshold for case 1. Meanwhile, using the Roger's Ratio method, the results show Case 4, which is caused by corona, partial discharge, and low to medium thermal temperature disturbances (<700°C). Based on the research, although there has been an increase in compound concentrations over the years, the test results indicate that both the transformer and its oil remain in normal and good condition. Thus, the transformer can continue to operate without the need for purification or oil replacement.

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