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Analysis of Transformer Oil Post-Flashover: DGA Testing and Diagnostic Approached

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ABSTRACT

Transformer oil (TO) is a coolant and insulator in transformers. Flashover contributes to the deterioration of TO, resulting in overheating oil within the transformer. Flashovers, characterized by abrupt electrical discharges in transformers, can produce gases in the insulating oil. Comprehending the alterations in gas content is vital for evaluating the well-being and state of the transformer. The gas analysis was performed utilizing the Total Dissolved Combustible Gas (TDCG), Doernenburg, and Roger's ratio method, specifically emphasizing gases obtained from the transformer oil and the gas space. The findings offer a significant understanding of the impact of flashovers on gas generation and assist in identifying potential problems within the transformer. All cycles exhibit TDCG values that surpass those of the original oil. The result of the flashover simulation conducted using BDV testing leads to an alteration in the gas composition within the TO. According to the TDCG results, the transformer is in condition I. Although the scenario arises during the actual operation of the transformer, the transformer can continue to function normally by taking certain precautions, specifically, being cautious, analyzing the presence of individual gases, and assessing the impact of the load. Both analyses conducted using the Doernenburg and Roger's ratio method conclude no evidence of any fault or error. Conducting flashover simulation through the BDV test will modify the gas composition in the oil, but it will not have any lethal consequences.

Keywords: Breakdown voltage, Dissolved gas analysis, Mineral oil, Post-flashover, Transformer Oil

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1. INTRODUCTIONS

Electric transformers are essential for transmitting electrical energy between different locations in the power system. For maximum efficiency, these transformers utilize insulating oil, specifically Uninhibited Naphthenic-Based Mineral Oil (UNBMO-Nynas nitro libra), to ensure effective cooling and insulation within the transformer system. Nevertheless, transformers are vulnerable to flashovers, which are inadvertent electrical discharges that can cause significant harm during operation. Flashovers can produce elevated temperatures and modify the state of insulating oil, including its gas composition. However, the current body of literature does not contain significant research specifically examining the influence of flashovers on the gas composition within this insulating oil. Electric transformers play a crucial role in facilitating the transfer of electricity within power systems. They depend on insulating oils such as UNBM-Nynas nitro libra for effective cooling and insulation. Nevertheless, flashovers present a potential hazard as they can result in unintended electrical discharges and potentially harm the transformer by modifying the condition of the oil, particularly its gas composition. Despite their importance, the existing

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literature has limited research on the specific impact of flashovers on gas formation within these oils.

Electric transformers are essential for transmitting electrical energy between different locations in the power system. Transformers are costly equipment, so efforts should be made to minimize transformer failures. Figure 1 shows an exponential graph predicting a 50% failure rate for transformers at the age of 50 years and reaching 100% at 80 years of operation [1]. Transformer failures initially occur due to flashovers caused by the deterioration of insulation properties in transformer oil. Flashovers can produce elevated temperatures and modify the state of insulating oil, including its gas composition. However, the current body of literature needs to contain significant research, specifically examining the influence of flashovers on the gas composition within this insulating oil.

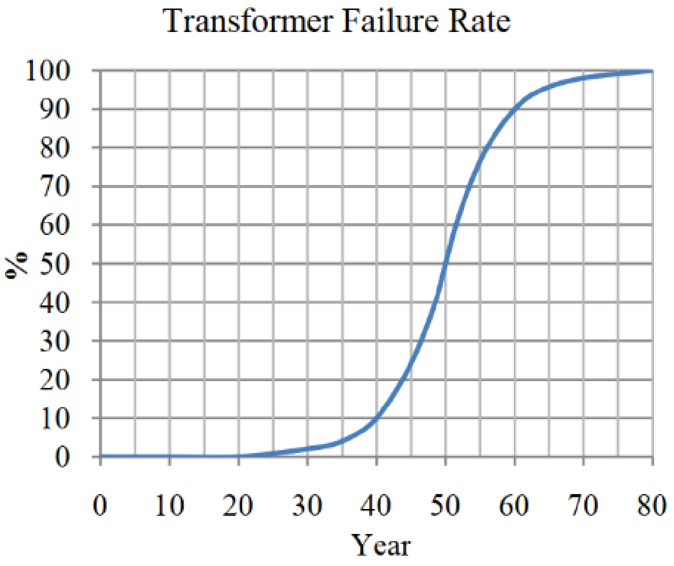

Figure 1. Prediction of transformers failure rate [1]

Flashovers present a potential hazard as they can result in unintended electrical discharges and potentially harm the transformer by modifying the condition of the oil, particularly its gas composition. Despite their importance, the existing literature needs more research on the specific impact of flashovers on gas formation within these oils. A comprehensive understanding of this influence is essential for the maintenance and optimization of transformers. Undetected flashovers from the beginning can cause fatal damage to transformers. One way to detect flashovers is through Dissolved Gas Analysis (DGA) testing [2-4]. DGA testing is conducted to determine the content of gases that appear in transformer oil (TO). TO is a crucial component responsible for the lifetime of transformers. TO serves as a cooling fluid and insulation medium in transformers. TO is divided into mineral oil (MO), synthetic oil, and organic oil [5]. Due to its widespread availability and relatively low cost, MO has been widely used as insulation and cooling oil. Most large power transformers worldwide employ MO as the insulation fluid [6, 7]. MO contains open-chain hydrocarbons (paraffin), saturated ring hydrocarbons (naphtha), and aromatic hydrocarbons [8, 9], and it has a highly complex chemical structure, as illustrated in Figure 2. The operational conditions of the transformer cause a gradual degradation in the quality of MO. Therefore, early detection of oil quality is crucial to reduce potential losses in transformer operations. An early detection method is to measure the gas content in MO. Gases in the transformer are formed due to decomposition in the MO. These gas contents include Methane (CH_4), Acetylene (C_2H_2), Ethylene (C_2H_4), Ethane (C_2H_6), Hydrogen (H_2), Carbon Monoxide (CO), which are commonly classified as combustible gases [6, 10-13].

These gases can form due to the pressure-temperature relationship, where these gases may emerge. The relationship of partial pressure to thermal equilibrium as a function of temperature can be observed in Figure 3. Once the gas content is known, the type of failure present in the transformer can be analyzed.

There are various methods for diagnosing failure types in TO, including the Dornenburg-Rogers Ratio, and

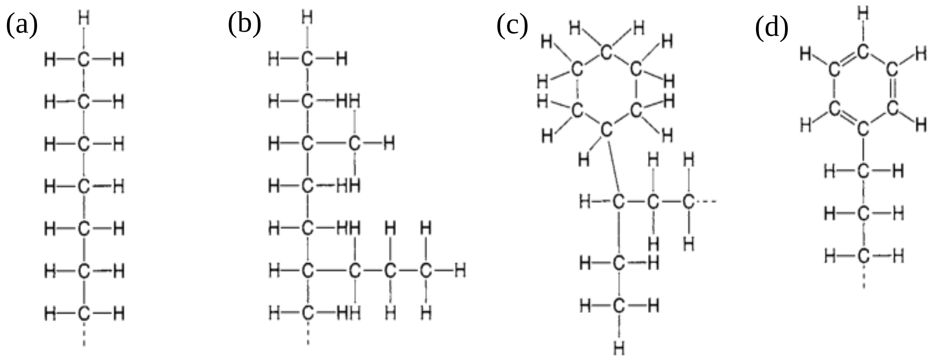

Figure 2. Types of mineral oil; (a) straight-chain paraffinic, (b) branched-chain paraffinic, (c) naphthenic, and (d) aromatic [14].

Total Dissolved Combustible Gas (TDCG) [3, 15]. The analysis results are a reference for determining the oil condition, potential failure types, and the necessary actions for transformer operation. Research on DGA in TO has been extensively conducted. M. Chakraborty et al. [10] demonstrated in their study that heating MO at 150°C for 168 hours in a hot air circulating oven increased the oil's hydrocarbon gas content. Studies using inhibited and uninhibited naphthenic oil were also carried out by B. Christian and A. Gläser [12]. The research showed that all gas contents increased with the number of flashovers conducted. A Hybrid analysis method on gas content in MO was conducted by L. Londo et al. [1], and the research results showed an improvement in accuracy by 9% compared to the simple Key Gas Method.

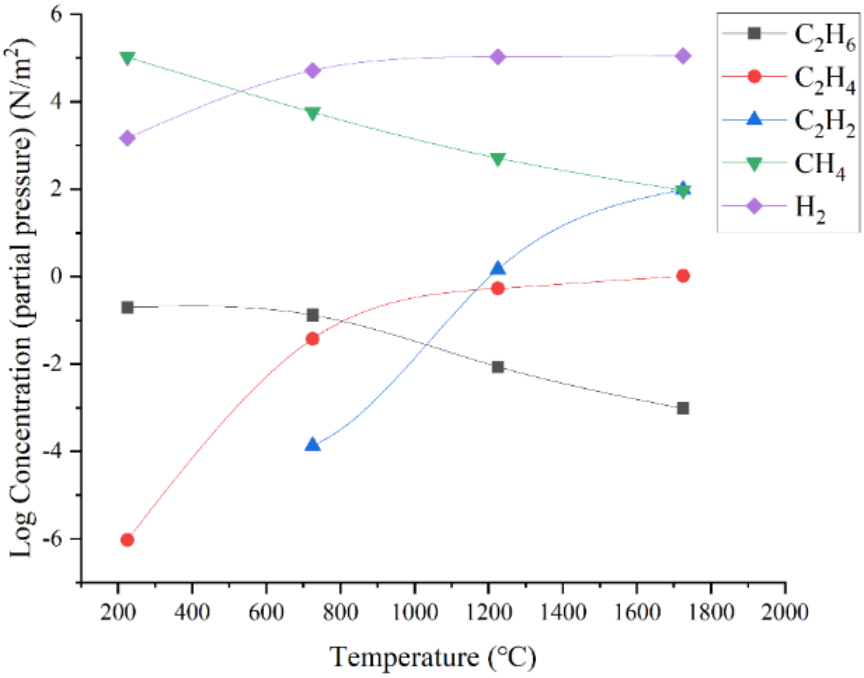

Figure 3. The relationship of partial pressure in thermal equilibrium as a function of temperature [16]

Prior research has yet to extensively examine the examination of gas in TO following a flashover event. The knowledge gap in this situation pertains to the limited comprehension of how flashover impacts the makeup of gases in Uninhibited Naphthenic-Based Mineral Oil (UNMO) explicitly. This comprehension could enhance our knowledge of the transformer's condition and performance after a flashover event. This study examines the impact of flashover, which has received limited attention in analyzing gas in UNMO, on the formation and production of gases in the oil. The study employs the breakdown voltage (BDV) method to evaluate the composition of gases produced following a flashover, thereby providing novel insights into transformer failure potential damage. These samples will be analyzed for the gas content in TO using a hybrid method, including the TDCG, Doernenburg ratio, and Roger's ratio.

2. METHOD

2.1. The Transformer Oil

The transformer oil used is UNMO Nynas nitro libra. The selected oil sample has undergone purification once and is in a newly purified condition. The choice of this sample is based on its high-quality state, adhering to the standards specified in IEC 60296 [17]. 1000 ml of the sample is stored in a covered measuring bottle to prevent contamination from the surrounding air. The flashover simulation is conducted through BDV testing by the IEC 60156 standard [18]. The apparatus employed is the Oil Breakdown Voltage Tester, BAUR type DTA 100 C. The electrode has a mushroom shape with a diameter of 12.5mm, and the electrode gap is 2.5mm [18]. The oil is introduced into the testing apparatus and stirred with a five-minute magnetic stirrer. The testing voltage rate utilized is 2Kv.s^{-1} until breakdown occurs. One testing cycle involves six voltage shots, and the testing apparatus automatically records the average breakdown. The testing involves 5 and 10 cycles (number of flashovers).

2.2. Flashover Simulation

The TO that has undergone the flashover simulation is then subjected to DGA testing to determine the impact of gas content after the flashover simulation. DGA testing is conducted according to the IEC 60599 standard [19]. The equipment used is the Gas Chromatograph from Henan Zhongfen, type ZF-301B. A sample of 40 ml is used, taken with a 100 ml syringe. Careful attention is given to ensure no air bubbles in the sample. A gas carrier of 10 ml is extracted from the chromatographic analysis instrument using a 10 ml syringe, which is then injected into the gas carrier hole inside the testing instrument. The obtained gas carrier is injected into the provided oil sample. Now infused with the gas carrier, the sample is placed in the shaker machine. This process runs for 30 minutes, shaking for 10 minutes and then allowing it to settle at a temperature of 50 ºC, which is maintained for 20 minutes. The process is considered complete when the instrument's alarm activates. After the shaker process, the gas mixture is transferred from a 40 ml syringe to a 5 ml syringe. 1 ml sample of the gas mixture is extracted using a 1 ml syringe from the 5 ml syringe. This gas sample is then inserted into the Chromatographic Analysis instrument, and the process continues until the test results are displayed in graphical form. All these steps are carried out for each sample. The results of the DGA testing reveal the content of gases dissolved in the oil. These results are then analyzed to assess the quality and potential causes of failure in the transformer. The analysis findings are crucial in determining the appropriate maintenance steps. The analysis methods employed in this study include the TDCG, Doernenburg ratio and Roger's ratio. The DGA outcomes provide information regarding the quantity of gas dissolved in the TO. In order to identify possible factors that may have contributed to the failure of the transformer, these findings are subjected to rigorous examination to determine the quality of the oil.

TDCG is an essential technique in transformer maintenance that enables the timely detection of potential issues. Through the analysis of the gas dissolved in TO, we are able to monitor the quantity of gas that is generated as a result of regular processes or damage. This enables technicians to accurately detect any damage or malfunction in the transformer prior to it escalating into a more severe issue, thereby facilitating prompt repair or replacement measures to uphold the transformer's optimal performance. The limitations of dissolved gas conditions are presented in Table 1. Parts Per Million (ppm) represents the gas concentration, calculated using Equation (1) [1, 20].

$$\text{TDCG} = H_2 + CH_4 + C_2H_2 + C_2H_4 + C_2H_6 + \text{CO} \tag{1}$$

Table 1. Limitation of dissolved gas conditions [20]

No.	Gas type	Condition I	Condition II	Condition III	Condition IV
1	H_2	100	100 - 700	701 - 1800	>1800
2	CH_4	120	121 - 400	401 - 1000	>1000
3	C_2H_2	35	36 - 50	51 - 80	>80
4	C_2H_4	50	51 - 100	101 - 200	>120
5	C_2H_6	65	66 - 100	101 - 150	>150
6	CO	350	351 - 570	571 - 1400	>1400
7	CO_2	2500	2500 - 4000	4001 - 10000	>10000
8	TDCG	720	721 - 1920	1921 - 4530	>4630

By analyzing the results obtained from conditions I-IV in Table 1, one can ascertain the operating procedures outlined in Table 2. TDCG levels regulate four distinct conditions, each with its prescribed operating procedures. Condition I authorize the continuation of normal operations with caution, individual gas analysis, and determination of load dependence. Condition II prescribes prudence, individual gas analysis, and evaluation of load dependence. Condition III requires implementing stringent measures, including individual gas analysis, outage planning, and notification to the manufacturer. Condition IV, which entails individual gas analysis, outage planning, manufacturer notification, potential service removal consideration, and manufacturer advisory, necessitates the utmost caution. These conditions establish explicit procedures by TDCG levels to guarantee safety and suitable conduct throughout operations.

Table 2. Actions based on TDCG [20]

TDCG Levels	Operating procedures
Condition I	– Continue normal operation – Exercise caution – Analyze for individual gases – Determine load dependence
Condition II	– Exercise caution – Analyze for individual gases – Determine load dependence
Condition III	– Exercise extreme caution – Analyze for individual gases – Plan outage – Advise manufacturer
Condition IV	– Exercise extreme caution – Analyze for individual gases – Plan outage – Advise manufacturer – Consider removal from service – Advise manufacturer

Diagnostic theory based on the principle of thermal degradation uses a series of ratios of major combustible gases as indicators of the type of fault. These ratios are denoted as R1-R5 and ratio values are calculated using Equation (2)-(6) [20].

$$R1 = \frac{CH_4}{H_2} \tag{2}$$

$$R2 = \frac{C_2H_2}{C_2H_4} \tag{3}$$

$$R3 = \frac{C_2H_2}{CH_4} \tag{4}$$

$$R4 = \frac{C_2H_6}{C_2H_2} \tag{5}$$

$$R5 = \frac{C_2H_4}{C_2H_6} \tag{6}$$

The Doernenburg ratio method identifies three prevalent types of errors. This method employs gas concentrations to calculate R1, R2, R3, and R4, which are subsequently compared to the limiting values (L1) specified in Table 3..

Table 3. Limit concentration of dissolved gas [16]

Key gas	**Concentrations (L_1) [µL/L (ppm)]**
Hydrogen	100
Methane	120
Carbon monoxide	350
Acetylene	1
Ethylene	50
Ethane	65

Figure 4 illustrates the sequential process of the Doernenburg Method. The Doernenburg ratio method is applied by examining gases extracted exclusively from the TO. The process is subsequently duplicated for gases acquired from the gas space or gas relays, with distinct threshold values for the proportions customized to the attributes of the gas space as outlined in Table 4.

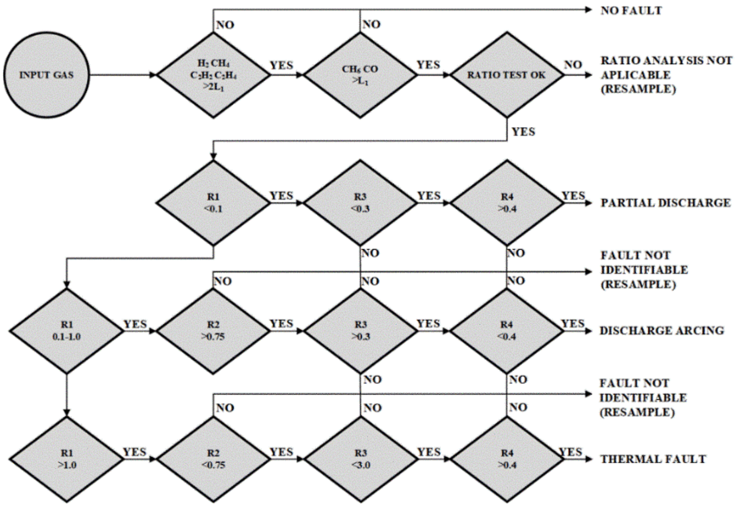

Figure 4. Flowchart of the Doernenburg Ratio Method [16]

Table 4. Ratios for key gases Doernenburg [16]

Case	**R1**		**R2**		**R3**		**R4**		**Suggested fault diagnosis***
	Oil	**Gas space**	**Oil**	**Gas space**	**Oil**	**Gas space**	**Oil**	**Gas space**	
0	>1.0	>1.0	<0.75	< 1.0	<0.3	<1.0	>0.4	>0.2	TD
1	< 0.1	< 0.01	not significant		<0.3	<1.0	>0.4	>0.2	PD
2	>0.1 to <1.0	>0.01 to <0.1	>0.75	>1.0	>0.3	>0.1	<0.4	<0.2	A

Noted+ *TD= Thermal decomposition, PD=Partial discharge (low intensity PD), A=Arching (high intensity PD)

2.3. Doernenburg and Roger's Ratio

Roger's ratio method, which analyzes gases within transformer oil, is an indispensable diagnostic tool for transformers. It focuses on three gas ratios—R1, R2, and R5—in contrast to the Doernenburg method to detect thermal degradation. This detection is fundamental to its operation. The correlation between failure investigations and gas ratios lends credibility, which is reinforced by many cases that augment dependability. The procedural sequence of the method is illustrated in Figure 5, which facilitates the identification of faults and the planning of maintenance. The values of gas ratios and suggested diagnoses are presented in Table 5. Every ratio corresponds to a distinct category of faults or conditions, which aids in the process of identifying and characterizing problems within transformers.

Table 5. Roger ratios for key gas [16]

Case	R_1	R_2	R_5	Suggested fault diagnosis
0	> 0.1 to <1.0	< 0.1	< 1.0	Unit normal
1	< 0.1	< 0.1	< 1.0	Low energy density arcing
2	0.1 to 1.0	0.1 to 3.0	> 3.0	Arcing- High energy discharge
3	> 0.1 to <1.0	< 0.1	1.0 to 3.0	Low temperature thermal
4	> 1.0	< 0.1	1.0 to 3.0	Thermal < 700 ℃
5	> 1.0	< 0.1	> 3.0	Thermal >700 ℃

Roger's ratio method is an essential diagnostic instrument utilized for transformers, which examines the gases generated in the transformer oil. In contrast to the Doernenburg method, this approach emphasizes three specific gas ratios, namely R1, R2, and R5, to detect thermal degradation occurring within the transformer. The fundamental principle of the method is predicated on this detection mechanism. The basis for its credibility and validity is the correlation that exists between gas ratios and the results obtained from failure investigations. This correlation is derived from many cases, enhancing the dependability and credibility of this diagnostic methodology. The procedural sequence inherent to Roger's ratio method is graphically represented in Figure 5. This sequence provides a comprehensive framework for identifying transformer faults and organizing subsequent maintenance efforts.

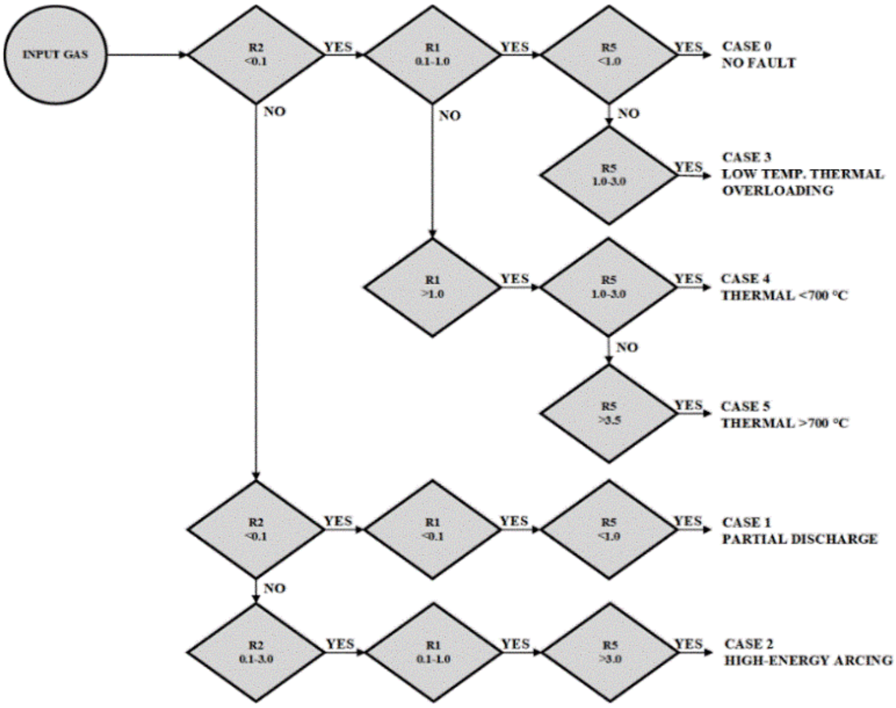

Figure 5. Flowchart of the Roger's ratio Method [16]

3. RESULT AND DISCUSIONS

3.1. Breakdown Voltage (BDV) Analysis

BDV analysis is exhaustively described, and the results are discussed in conjunction with the research findings reported in [21-24]. Figure 6 (a) provided the evident that sample 1 in the second testing cycle exhibited the lowest BDV value of 78.9 kV among the two tested samples. Conversely, sample 2 in the third testing cycle displayed the highest BDV value of 85.6 kV. Sample 1 and Sample 2 have respective BDV averages of 83.25 kV and 81.76 kV when the average is computed. The test results are illustrated in the figure compared to other investigations that employed the same methodology and instrument, namely a 2.5 mm electrode gap and a 2 kV s-1 voltage rate at room temperature. In contrast to specific previously published references [21-24], samples 1 and 2 in this investigation have greater BDV values, as shown in Figure 6 (b). It can be attributed to the purified and transformer-ready state of the samples utilized in this study.

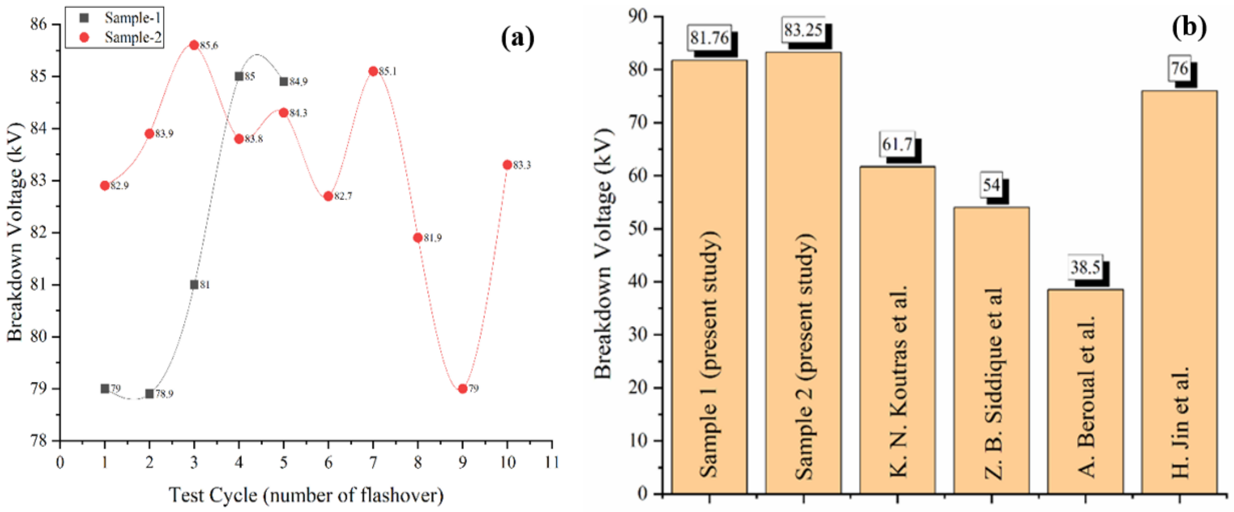

Figure 6. BDV analysis: (a) BDV test result, and (b) BDV comparison results.

3.2. Dissolved Gas Analysis (DGA)

The primary aim of DGA was to assess the influence of flashovers on gas concentrations accurately. After the simulation, a thorough gas composition analysis was performed on the samples utilizing the DGA test. The results assiduously gathered for this analysis are displayed in Table 6. Consistent with the findings of B. Christian and A. Glaser [12], Table 6 demonstrates that the frequency of flashovers causes an increase in the concentration of nearly all gases. Nevertheless, slight variations in CO_2 and C_2H_2 indicate a reduction. This inconsistency may be attributed to a considerable proportion of the carbon atom transforming CO and CH_4 compounds, resulting in a substantial escalation. Comprehending these fluctuations is of the utmost importance in differentiating the intricate reactions during flashovers and the resultant effects on the gas composition inside transformers. Moreover, this understanding facilitates the enhancement of predictive maintenance approaches to reduce the likelihood of transformer malfunctions.

Table 6. DGA test result

Test Cycle (number of flashover)	H_2	CO	CO_2	CH_4	C_2H_2	C_2H_4	C_2H_6	O_2	N_2
0	8.53	0.00	242.71	0.52	0.00	0.28	0.00	0	0
5	0.00	0.00	766.35	3.30	3.92	0.43	5.42	0	0
10	2.40	40.33	185.29	17.26	2.78	6.84	7.93	0	0

The TDCG results for each test cycle are illustrated in Figure 7, which demonstrates a steady upward trend. The utilization of this visualization enhances the understanding of the relationships that exist between flashover incidents and changes in gas composition—equation 1. Calculations of TDCG values are facilitated by data obtained from DGA testing. TDCG values consistently surpass those of the initial oil throughout all cycles, as illustrated in Figure 7. The escalation observed in the transformer oil can be attributed to the flashover simulation induced by the BDV testing, which caused changes in gas concentrations. Based on the TDCG results presented in Figure 7, and the conditions outlined in Table 1, it can be concluded that the transformer conforms to the first condition. It permits continued operation of the transformer with the following precautions: exercising caution, conducting individual gas analysis, and evaluating load dependence if such an incident occurs during regular operation.

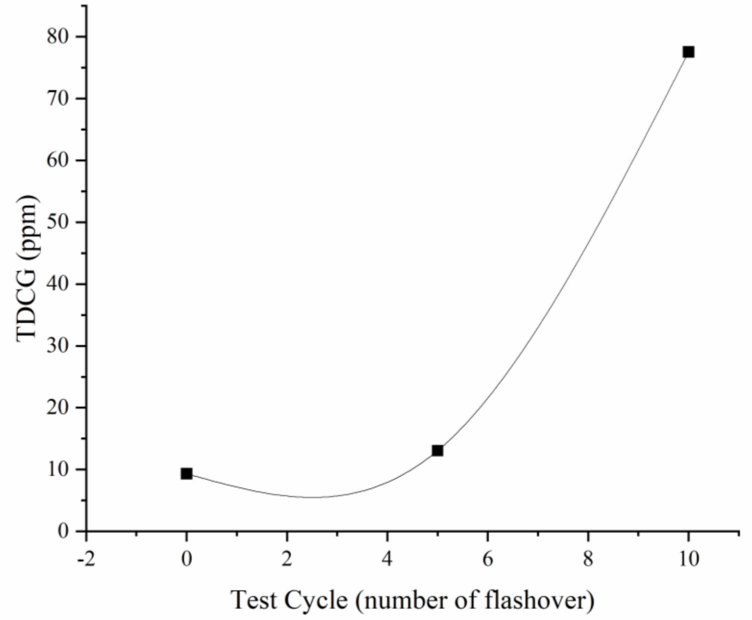

Figure 7. TDCG result

3.3. Doernenburg and Roger's Ratio Analysis

Doernenburg and Roger's ratio methods employ gas analysis in transformer oil to detect faults or irregularities within transformer systems. These techniques expect to identify problems such as insulation breakdowns, thermal degradation, and electrical faults by analyzing particular gas ratios. Identifying potential transformer malfunctions or deteriorations is facilitated by comparing these ratios to established thresholds or values. It enables proactive maintenance measures to be taken, thereby preventing system failures.

Regarding both approaches, ratio values are crucial. The ratios computed from Equations (2)-(6) are presented in Table 7 [20]. Table 6 notably indicates that the H_2, CH_4, C_2H_2, and C_2H_4 concentrations across all test cycles are lower than $2L_1$ (Table 3). Therefore, calculating ratios using Equations (2)-(6) is unnecessary, as the Doernenburg method signifies a "No Fault" scenario. Table 7 consistently displays a "No Fault" status for all oil cycles, whereas Roger's method, centered on R1, R2, and R5, resembles the Doernenburg approach.

Table 7. Doernenburg and Roger's Ratio values

Test Cycle	R1	R2	R3	R4	R5
0	0,060961	0	0	~	~
5	~	9,116279	1,187879	1,382653	0,079336
10	7,191667	0,406433	0,161066	2,852518	0,862547
15	0,100519	~	1,652582	1,21875	0

4. CONCLUTIONS

The simulated TO is subsequently subjected to DGA analysis while undergoing a flashover to ascertain the impact of gas content after the simulation. The DGA analysis results offer valuable information regarding the gas composition inherent in the oil. The results above are subsequently assessed to ascertain the transformer's quality and identify potential factors contributing to its malfunction. The outcomes of the analysis are critical in order to determine which maintenance procedures are required. The analysis methods employed in this investigation included the TDCG, Doernenburg ratio, and Roger's ratio. TDCG values produced by each cycle are higher than those of the initial oil. Due to the BDV testing-based flashover simulation, the gas concentrations in the TO were modified. The condition I is the rating assigned to the transformer by the TDCG results. Should this incident transpire during the operational phase of the transformer, it is possible to restore normal operations while observing the following precautions: exercising caution, performing individual gas analyses, and determining load dependence. Both the Doernenburg ratio and Roger's ratio analyses yield the result "No Fault." Therefore, by utilizing the BDV test to simulate flashovers, the gas composition of the oil will be altered, but not in a way that could potentially lead to catastrophic outcomes..

AUTHOR’S DECLARATION

Authors’ contributions and responsibilities

The authors have played crucial roles in conceiving and designing the study. They actively engaged in data analysis, interpretation, and discussions of the results. All authors have thoroughly reviewed and approved the final manuscript, underscoring their collective and individual contributions to the research endeavor.

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Availability of data and materials

All data from this study are accessible through the authors.

Competing interests

The authors declare no competing interest.

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