International Journal of Electrical and Computer Engineering (IJECE)
Vol. 13, No. 4, August 2023, pp. 3672~3685
ISSN: 2088-8708, DOI: 10.11591/ijece.v13i4.pp3672-3685

Analysis of interference methods on transformers based on the results of dissolved gas analysis tests

Yulianta Siregar, Timothy Juan Hartanto Lumbanraja
Department of Electrical Engineering, Faculty of Engineering, Universitas Sumatera Utara, Medan, Indonesia

Article Info

Article history:

Received Sep 7, 2022
Revised Dec 12, 2022
Accepted Dec 17, 2022

Keywords:

Dissolved gas analysis
Electrical failure
Gas ratio
Power transformer
Thermal failure

ABSTRACT

In the operation of the power transformer, several maintenance efforts must be made to ensure the condition of the transformer is in good condition. The problems that usually arise are a thermal failure and electrical failure. The use of insulating media such as transformer oil and transformer insulation paper can be disrupted by this failure. Dissolved gas analysis, which identifies the types and concentrations of dissolved gas in transformer oil, can reveal details on fault indicators in power transformers (DGA). In this study, we used the interpretation of the IEEE std 2008-C57.104 (total dissolved combustible gas (TDCG), key gas, Rogers ratio method), the interpretation of IEC 2015-60599 (Duval triangle and basic gas ratio method), and the IEEE Std 2019-C57.104 interpretation (Duval pentagon method). The outcome of the DGA test is used to determine the conditions and indications of disturbances in the transformer for power. Using various gas analysis techniques also impacts the outcome of the fault indication. This variation has affected the types of gas used in the computation and the gas concentration limit value estimation. After the gas analysis, it was found that the oil purification process was also proven to reduce the concentration of combustible gases.

Corresponding Author:

Yulianta Siregar
Department of Electrical Engineering, Faculty of Engineering, Universitas Sumatera Utara
Medan, Indonesia
Email: julianta_srg@usu.ac.id

1. INTRODUCTION

The need for electrical energy in Indonesia is increasing along with technology and industry development. The existing electric power system must always be considered and developed to ensure the availability of electrical energy. One of the crucial parts of the electrical power system is the transformer, yet neglecting it can result in overheating, corona, and arcing, affecting how well the transformer performs. The oil in the transformer functions as a coolant and insulator. The presence of gas in the transformer oil might potentially result in failure of the transformer. The impact of failure on the transformer is ascertained using the dissolved gas analysis technique. A dissolved gas analysis (DGA) test is performed to evaluate the transformer's condition [1].

Due to the breakdown of insulating oil and paper, the DGA method uses different concentrations of dissolved gases in transformer oil. DGA has become widely accepted as a technique for identifying transformer defects that are only beginning [1]. The gas produced and the usual or dominating gas at different temperatures can be used to identify faults in transformer oil. These gases include methane (CH_4), hydrogen (H_2), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon dioxide (CO_2), and carbon monoxide (CO) [2]. When the transformer works continuously, it causes the compound to break up into C-H elements. The formation of these hydrocarbon gases causes thermal failure, partial discharge, and arcing, which can trigger fires. DGA is a technique for determining the quantities or values of the hydrocarbon gases produced due to these anomalies.

Previous studies on DGA, such as oil-immersed power transformer fault diagnosis using DGA. According to the interpretation of IEEE Standard 2008-C57.104 (total dissolved combustible gas (TDCG), Key gas method, Doernenburg ratio, and Rogers ratio), DGA testing is used in this study to determine the type of defect in the transformer power. And then IEC 2015-60599 (Duval triangle, basic gas ratio, and CO_2/CO ratio). This experiment still found thermal failure in the power transformer [3]. "Duval triangle and Rogers ratio prediction used for the analysis of 132/33 kV 15 MVA power transformer dissolved gas using the Transport-X Kelman Kit", it researched power transformers using the dissolved gas analysis method. The DGA method used in this study is the Duval triangle and Rogers ratio. The results obtained are that in sample I, there is an indication of thermal failure due to an increase in oil temperature above 700 °C, and in sample II there is no indication of failure [4]. "Using traditional methods, dissolved gas analysis and evaluation in electric power transformers", researched dissolved gas analysis using conventional methods. In this study, a comparison of several dissolved gas analysis methods was carried out. Key gas method, Doernenburg ratio, Rogers ratio, IEC 60599, Duval triangles, Duval pentagons, and Mansour pentagons are some techniques employed. Low energy discharge (D1), high energy discharge (D2), partial discharge (PD), low overheating (T1), medium overheating (T2), and high overheating (T3) are the classifications of failures employed in this comparative approach. The findings demonstrate that the best techniques for more thorough fault diagnostics in transformers are Duval pentagons and Duval triangles [5]. "Case studies for the diagnosis of transformer faults using dissolved gas analysis," study on the application of the dissolved gas analysis technique to diagnose transformer failure. This research uses the key gas method, the Doernenburg ratio, and the Rogers ratio [6]. In this study, data were taken from 2 case studies. The first case study is a 250 MVA, 15.75/420 kV, 3-phase transformer with an oil forced air forced (OFAF) cooling system. The second case study is a 290 MVA, 18/240 kV, 3-phase transformer with OFAF cooling [7]. The results obtained in case study 1 are based on the key gas method. The transformer experienced a type of electrical partial discharge failure due to the dominance of H_2 gas. Based on the Rogers ratio and Doernenburg ratio method, the transformer experienced a partial discharge failure type. The utility personnel finally confirmed that the transformer experienced a partial discharge type of failure. The results obtained in case study 2 are based on the key gas method. Due to C_2H_2 dominance in the gas, the transformer experienced a thermal-oil fault type. Based on the Doernenburg ratio method, the transformer experienced a thermal decomposition failure. According to the Rogers ratio approach, the transformer encountered a thermal fault-type failure with t>700 °C. The transformer had a type of thermal fault failure, which was the conclusion that was finally validated by the utility personnel.

Based on the research described above. In this study, the examination of transformer disturbances and the DGA test use the interpretation of the IEEE std 2019-C57.104 [8] TDCG, key gas, and Rogers ratio), IEC 2015-60599 [9] (Duval triangle and basic gas ratio), and IEEE Std 2019-C57.104 (Duval pentagon method) [10], and the research location in power transformer plant (PPTR) at PT. Indonesia Asahan Aluminum, Indonesia.

2. PROPOSED METHOD

2.1. Transformer

A transformer is a static electrical device in which a magnetic circuit and winding consisting of 2 or more windings, by electromagnetic induction, transform power (current and voltage) in an alternating current (AC) system to another current and voltage system that works at the same frequency. Ampere's law and Faraday's induction, which state that changes in current or electric fields can generate magnetic fields and that changes in magnetic fields or magnetic field fluxes can produce induced voltages, are the electromagnetic principles that the transformer relies on [11]. The electromotive force relationship can be used by (1), (2).

$$e = -N\frac{d\Phi}{dt} \quad (1)$$

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} = \frac{I_s}{I_p} \quad (2)$$

In (1) and (2), N is number of turns, e is electromotive force (Volt), $\frac{d\Phi}{dt}$ is rate of change of magnetic flux (Weber/sec).

2.2. DGA evaluation using total dissolved combustible gas

The entire volume of combustible gas produced is used in the TDCG method to assess the failure of transformer insulating materials. In this strategy, the total gas volume is a proxy for the transformer disturbance. According to this approach, there are four states for the transformer depending on the gas volume. The metrics used to gauge the transformer's condition are based on the concentration of each gas separately and the sum of all combustible gas concentrations. The value of the dissolved gas concentration limit to assess the condition of the transformer oil is shown in Table 1 [12].

The TDCG method in each condition is based on the condition and disturbance in the transformer. The explanation of each condition of the TDCG method is as follows [10]. The transformer is in good working order if the TDCG is below this threshold in condition 1. An investigation must be conducted immediately if one of the gases exceeds this level limit. The fact that condition 2 is TDCG at this concentration means that the explosive gas level has risen above the safe limit. An investigation needs to be done immediately if any of the gases surpass the limit at this level. To obtain the trend, behave following the procedure (tendency). There may have been a disruption in this state. At this level, condition 3 is TDCG, which denotes a high degree of decomposition. Immediately after noticing that one of the gases has exceeded this threshold limit, an investigation is conducted. There may have been a disruption in this state. Condition 4 is TDCG that has exceeded this limit indicates that there has been a very high level of deterioration. If we continue to operate directly on the transformer, it can cause damage to the transformer [13].

Table 1. Dissolved gas concentration limit

Status	Limit of dissolved gas concentration [μL/L (ppm)]							
	Hydrogen (H_2)	Methane (CH_4)	Acetylene (C_2H_2)	Ethylene (C_2H_4)	Ethane (C_2H_6)	Carbon Monoxide (CO)	Carbon Dioxide (CO_2)	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	4001-10.000	1921-4630
Condition 4	>1800	>1000	>35	>200	>150	>1400	>10.000	>4630

* The TDCG value does not include CO_2 gas because it is not a flammable gas

2.3. Calculation of combustible gas formation rate

Calculating the rate of explosive gas production is crucial since it affects the transformer's stability. The rate at which flammable gas formation occurs >2.8 L (0.1 ft^3) per day in the transformer may indicate that the transformer is experiencing an internal active fault. Take the sum of the concentrations [μL/L (ppm)] of all combustible gases (all but CO_2, O_2, and N_2) in the first and second samples to determine the rate of evolution of combustible gases, then use (3) [12]–[14].

$$R = \frac{(S_T - S_0) x\ V\ x\ 10^{-6}}{T} \tag{3}$$

where R is gas formation rate (liter/day), S_0 is first sample (microliter/liter or ppm), S_T is second sample (microliter/liter or ppm), V is oil volume (liters), T is time (day).

2.4. Key gas method

To evaluate the failure, this key gas approach needs six primary gas concentrations, including H_2, CH_4, C_2H_2, C_2H_4, and C_2H_6, as well as CO. The composition of the greatest individual gas amount determines whether the transformer will fail using the key gas approach. Four categories of failures in transformers using the key gas approach are recognized: electrical partial discharge, electrical arcing, thermal oil, and thermal cellulose [15], [16].

$$\%C_2H_4 = \frac{100C_2H_4}{CO + H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2} \tag{4}$$

$$\%CO = \frac{100CO}{CO + H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2} \tag{5}$$

$$\%H_2 = \frac{100H_2}{CO + H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2} \tag{6}$$

$$\%\mathrm{C_2H_2} = \frac{100\mathrm{C_2H_2}}{\mathrm{CO} + \mathrm{H_2} + \mathrm{CH_4} + \mathrm{C_2H_6} + \mathrm{C_2H_4} + \mathrm{C_2H_2}} \tag{7}$$

2.5. Rogers ratio method

The rate of formation of combustible gas is an important calculation to determine the rate of formation of gas that can cause disturbances in the transformer. A combustible gas generation rate of >2.8 L (0.1 ft3) per day in the transformer may indicate that the transformer is experiencing an internal active fault, as shown in Table 2 [3], [5]. Meanwhile, three ratios are used in this approach, namely (R1, R2, and R5). The link between the outcomes of numerous failure investigations and gas analysis for each case demonstrates the validity of this methodology. Values for the three primary gas ratios that correspond to the recommended diagnosis are shown in Table 3 [16].

Table 2. Condition of TDCG

Condition	TDCG level (ppm)	TDCG value (ppm/day)	Sampling interval and operating procedure based on the gas formation rate	
			Interval Sampling	Operation procedure
Condition 1	≤720	<10	Every year	– Normal operation
		10–30	Every 4 Months	
		>30	Monthly	– Requires attention – Individual gas analysis – Determine the effect of loading on the rate of gas formation
Condition 2	721-1920	<10	Every 4 Months	– Requires attention
		10-30	Monthly	– Individual gas analysis
		>30	Monthly	– Determine the effect of loading on the rate of gas formation
Condition 3	1921-4630	<10	Monthly	– Requires extreme attention
		10-30	Weekly	– Individual gas analysis
		>30	Weekly	– Plan outages – Provide Information to the manufacturer
Condition 4	>4630	<10	Weekly	– Requires extreme attention
		10-30	Daily	– Individual gas analysis – Plan outages – Provide Information to the manufacturer
		>30	Daily	– Consider replacement – Provide Information to the manufacturer

Table 3. Condition of Rogers ratio

Case	R_2 C_2H_2/C_2H_4	R_1 CH_4/H_2	R_5 C_2H_4/C_2H_6	Failure diagnosis
0	<0.1	>0.1-<1.0	<1.0	Normal unit
1	<0.1	<0.1	<1.0	Low arcing energy density
2	0.1-3.0	0.1-1.0	>3.0	High arcing-discharge energy
3	<0.1	>0.1-<1.0	1.0-3.0	Low thermal temperature
4	<0.1	>1.0	1.0-3.0	Thermal <700 °C
5	<0.1	>1.0	>3.0	Thermal >700 °C

2.6. Duval triangle method

The values of three gases, CH_4, C_2H_4, and C_2H_2, are used as parameters in the Duval triangle method. The percentage value of each gas is transformed into the triangle coordinates. In this method, three types of failure can be detected: the failure zone is comprised of partial discharge, electrical failure (high and low arcing energy values), and thermal failure hotspots from various temperature ranges. In this method, the standard in IEC 60599 is used in a Duval triangle, as seen in Figure 1 [17].

The size of the intersection of the three coordinates based on the value representation of CH_4, C_2H_4, and C_2H_2 will serve as a proxy for the type of failure in the Duval triangle technique. These coordinates can be determined based on the formula in the following (8)-(10). In this abbreviation: PD is partial discharge, DT is combination of thermal fault and discharge, $D1$ is discharge of low energy, $T1$ is thermal fault, t<300 °C, $D2$ is discharge of high energy, $T2$ is thermal fault, 300 °C<t<700 °C, $T3$ is thermal fault, t>700 °C. Meanwhile, the boundary zone in the Duval triangle method is described in Table 4 [16].

$$\%C_2H_2 = \frac{100\,x}{x+y+z} \tag{8}$$

$$\%CH_4 = \frac{100\,z}{x+y+z} \tag{9}$$

$$\%CH_4 = \frac{100\,z}{x+y+z} \tag{10}$$

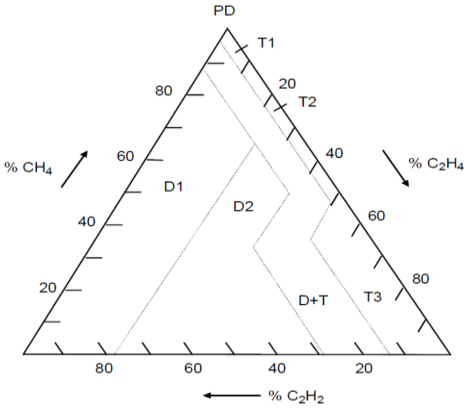


Figure 1. Duval triangle

Table 4. Zone boundary of Duval triangle

	Restriction Zone			
PD	98% CH_4			
D1	23% C_2H_4	13% C_2H_2		
D2	23% C_2H_4	13% C_2H_2	40% C_2H_4	29% C_2H_2
T1	4% C_2H_2	20% C_2H_4		
T2	4% C_2H_2	20% C_2H_4	50% C_2H_4	
T3	15% C_2H_2	50% C_2H_4		

2.7. Basic gas ratio method

In this test procedure, six types of failures occur in the transformer based on the basic gas ratio; (CH_4/H_2; C_2H_2/C_2H_4; C_2H_4/C_2H_6). In this method, the three ratios are symbolized by (R_1, R_2, and R_5). Table 5 depicts the correlation between the three gas ratio values and the transformer failure type [18].

Table 5. Zone boundary of Duval triangle

Cases	R_2 C_2H_2/C_2H_4	R_1 CH_4/H_2	R_5 C_2H_4/C_2H_6
PD	*Non-Significant*	<0,1	<0,2
D1	>1	0,1 - 0,5	>1
D2	0,6–2,5	0,1–1	>2
T1	*Non-Significant*	>1	<1
T2	<0,1	>1	1-4
T3	<0.2	>1	>4

2.8. Pentagon Duval method

The five primary hydrocarbon gases are H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, and the Duval pentagon technique presents them relative to one another. The five main hydrocarbon gases will combine to form a pentagon, as shown in Figure 2. Divide the amount of each gas by the total amount of the five gas components to get the relative contribution of each gas. The relative proportion of the five primary hydrocarbon gases is computed (in ppm) [19]–[22].

$$\%H_2 = \frac{H_2}{H_2+CH_4+C_2H_6+C_2H_4+C_2H_2} \tag{11}$$

$$\%CH_4 = \frac{CH_4}{H_2+CH_4+C_2H_6+C_2H_4+C_2H_2} \tag{12}$$

$$\%C_2H_6 = \frac{C_2H_6}{H_2+CH_4+C_2H_6+C_2H_4+C_2H_2} \tag{13}$$

$$\%C_2H_4 = \frac{C_2H_4}{H_2+CH_4+C_2H_6+C_2H_4+C_2H_2} \quad (14)$$

$$\%C_2H_2 = \frac{C_2H_2}{H_2+CH_4+C_2H_6+C_2H_4+C_2H_2} \quad (15)$$

$$x_i = \%Gas\ x\ cos\alpha \quad (16)$$

$$y_i = \%Gas\ x\ cos\ (90-\alpha) \quad (17)$$

$$C_x = \frac{1}{6A}\sum_{i-0}^{n-1}(x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i) \quad (18)$$

$$C_y = \frac{1}{6A}\sum_{i-0}^{n-1}(y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i) \quad (19)$$

$$A = \frac{1}{2}\sum_{i-0}^{n-1}(x_i y_{i+1} - x_{i+1} y_i) \quad (20)$$

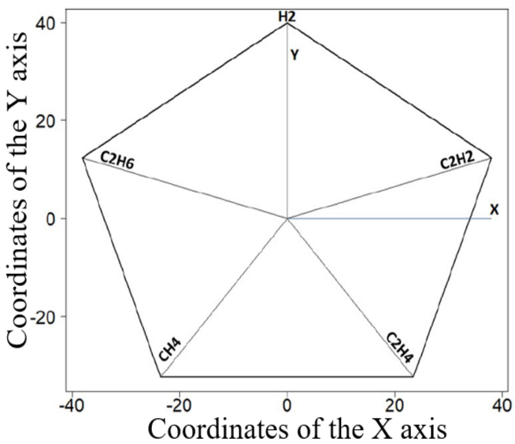


Figure 2. Original pentagon formed by five major hydrocarbon gases

3. METHOD

In this study, data from the DGA test findings in the form of gas concentrations H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, and CO dissolved in transformer oil were collected as part of the study technique. After data collection is complete, the analysis of the results of the DGA test and evaluation of disturbances in the transformer is carried out. Analysis of the DGA test findings and assessment of transformer faults using the interpretation of IEEE std 2008-C57.104 [10] (TDCG, Key gas, and Rogers ratio), IEC 2015-60599 [9], [23] (Duval triangle and basic gas ratio), and IEEE Std 2019-C57.104 [8] (Duval pentagon). The instrument used in this study is the portable dissolved gas analysis general electric (GE) Kelman Transport X. The information about the PPTR of PT Indonesia Asahan Aluminum comes from the results of the DGA tests.

The instrument used in this research is general electric Kelman Transport X, as seen in Figure 3. general electric Kelman Transport X uses the photo-acoustic spectroscopy method to perform DGA analysis with very high quality [4], [24], [25]. This tool can also provide measurements of all gases and their humidity. The gas extracted from the oil sample was measured using the infrared photo-acoustic spectroscopy method (semiconductor sensor for hydrogen). The specifications of the general electric Kelman Transport X as shown in Table 6.

The supplied sample bottle is equipped with a lid assembly, as shown in Figure 4. It incorporates an airtight compression fitting and a temperature probe equipped with a humidity sensor, all of which must be connected to the top panel of Transport X. Two Teflon-coated magnetic stirrers are provided; place one in the bottle before screwing the cap on. This magnet will be rotated in the bottle during the analysis cycle. Its presence is essential for the accurate operation of Transport X. Teflon-coated magnets should also be cleaned after each test. After use, the Teflon-coated magnets can be removed from the oil in the bottle using the supplied magnet retriever. In-line Teflon Filters are installed in the return and intake gas pipes. This filter is resistant to oil at operating pressure and protects the instrument from accidental spills and airborne dust.

These two filters must always be present; if a spill occurs and oil enters the gas analysis chamber from the photo-acoustic module, the instrument will require a new spectrometer. The Teflon filter is recommended to be replaced after every 20 samples.

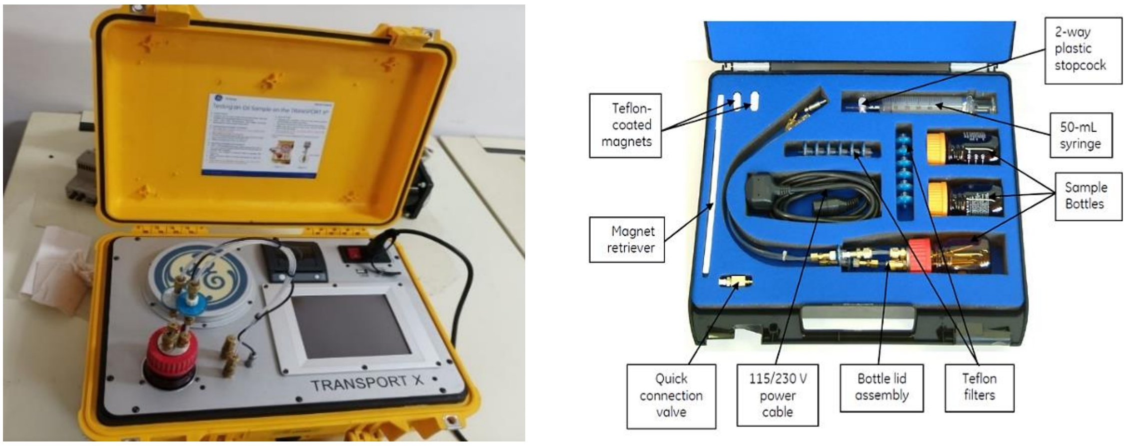


Figure 3. GE Kelman Transport X

Table 6. Specifications of Kelman Transport X

Fault Gas	Range Kalibrasi (ppm)	Parameter	Value/Meets
Hydrogen	5–5,000	Accuracy	• Gas: ±5% or ±2 ppm (whichever is greater) • Water: ±3 ppm
Carbon dioxide	2–50,000	Power Supply	115/230 Vac, 50/60 Hz, 40 W
Carbon monoxide	1–50,000	Fuse	F6.3 AH, 250 V, 5x20 mm
Methane	1–50,000	Battery	CR2032 lithium coin cell, 3 V
Ethane	1–50,000	Operating Temperature	5–40 °C (41–104 °F)
Ethylene	1–50,000	Operating Altitude	Maximum 2,000 m
Acetylene	0.5–50,000	Operating Pressure	760–1040 milibar
Water	0–100%	IP Rating	IP20 (operating)

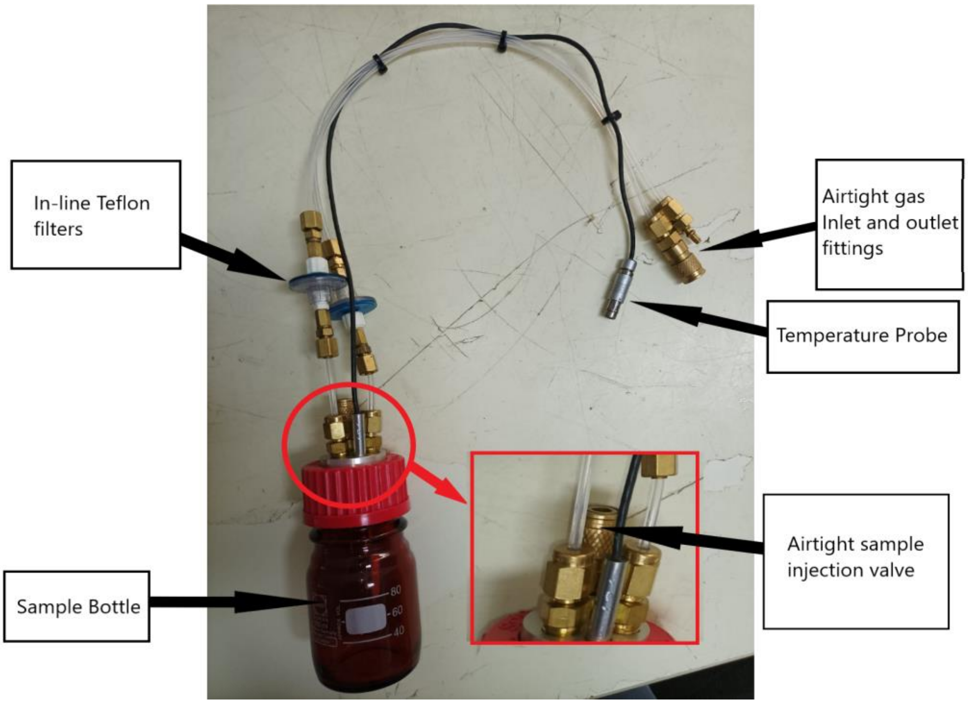


Figure 4. Sample bottle and lid assembly

Meanwhile, the power capacity of the transformer is 48 MVA with oil natural air forced (ONAF) cooling system. The type of oil used is Idemitsu transformer oil G (J), with a transformer tank capacity of 9,000 liters. The total weight of the transformer is 50,900 kg. The transformer at PT. Indonesia Asahan Aluminum is used to reduce the voltage from 33 kV received from the main transformer (MTR) to 11 kV to supply the factory load. This transformer has a capacity of 48,000 kVA. Table 7 provides information on the transformer specifications.

Table 7. Transformer specification

Item	Plant power transformer
Manufacture	Toshiba
Rated Capacity	48,000 kVA
Rated Voltage	33 kV/11 kV
Tap Changer	NVTC 1=34.5 kV
	NVTC 2=33.0 kV
	NVTC 3=31.5 kV
	NVTC 4=30.0 kV
Connection	Dyn11
	Neutral grounded by NGR
Impedance voltage	9.05%
Cooling Fan	8 Fans x 4
	(2 Back, 1 Right and 1 Left)
Type	Oil-immersed, ONAF

4. RESULTS AND DISCUSSION

4.1. Transformer failure evaluation based on TDCG method

Table 8 displays the outcomes of the DGA test performed on a 48 MVA power transformer. The outcomes of the DGA test show that the gas CH_4 and C_2H_6 have passed the limit of condition 1. DGA results also show that the gas level C_2H_6 has reached condition 4, which indicates that there has been deterioration in the transformer and a high risk of damage to the power transformer. The outcomes of the DGA test also show that the TDCG values in the first and second samples have reached condition 2. Other methods can find the results of this type of failure indication, and the concentration of each flammable gas dissolved in transformer oil is monitored by this TDCG method.

Table 8. Test results from DGA transformer

Parameter	January 23, 2020	August 14, 2020
Hydrogen (H_2)	34	5
Methane (CH_4)	99	195
Acetylene (C_2H_2)	0	0
Ethylene (C_2H_4)	16	14
Ethane (C_2H_6)	756	791
Carbon monoxide (CO)	62	81
Carbon Dioxide (CO_2)	1680	1994
Total Dissolved Combustible Gas (TDCG)	967	1081

Table 8 shows a decrease in each gas's ppm value on January 23, 2020. This is because the transformer overhaul and oil filtration were carried out the day before. These results indicate that the oil filtration process has been successfully carried out, namely with a low concentration of combustible gas values. The results of this filtration are also only temporary after the filtration process must be re-checked on the transformer parts, especially transformer isolation, according to the type of failure indication obtained.

4.2. Transformer failure evaluation based on key gas method

Figure 5 displays the outcomes of the DGA analysis using the key gas approach. The analysis of the key gas method results, namely on the January 23, 2020 sample, obtained a presentation of 1.6546% C_2H_4; 6.41158% CO; 3.51603% H_2, and 0% C_2 H_2. In the August 14, 2020 sample, the presentation was 1.2891% C_2H_4, 7.4585% CO, 0.4604% H_2 and 0% C_2H_2.

4.3. Transformer failure evaluation based on Rogers ratio method

According to the results of computations using the standard in Table 9 and the Rogers ratio method, the Rogers ratio approach cannot identify disturbances in this situation. In the calculation obtained, namely

R2<0.1, R1>1, the calculation results lead to cases 4 and 5. Table 9 displays the analytical findings using the Rogers ratio approach.

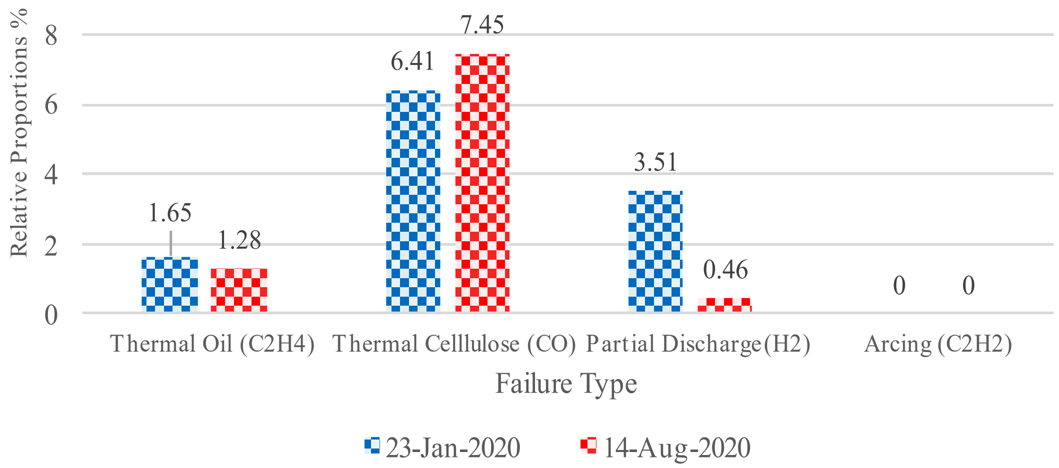


Figure 5. Name plate transformator

Table 9. Test results from the Rogers ratio method

Date	Failure Indication	R2 $\frac{C_2H_2}{C_2H_4}$	R1 $\frac{CH_4}{H_2}$	R5 $\frac{C_2H_4}{C_2H_6}$
Jan 23, 2020	Not detected	0 (<0.1)	2.91 (>1)	0.02 (<1)
Aug 14, 2020	Not detected	0 (<0.1)	39 (>1)	0.017

4.4. Transformer failure evaluation based on Duval triangle method

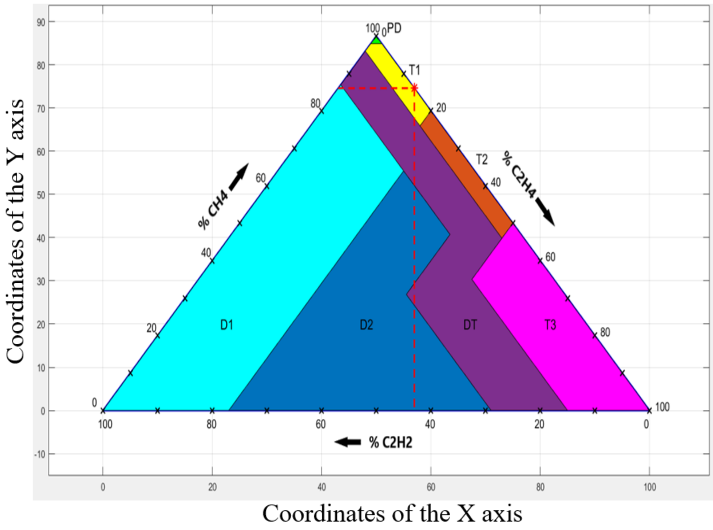
After calculating (1)-(3), the results of the relative presence of each gas are obtained, as shown in Table 10. After obtaining the presentation value of each gas, the transformation is carried out to triangular coordinates to facilitate the representation of the results in the MATLAB application. The calculation results are then converted into triangular coordinates according to (4) to facilitate visualization in the MATLAB application. The calculation results on the January 23, 2020 sample, namely (56.95 74.55 1) and the August 14, 2020 sample, are (53.34 80.79 1). Figures 6(a) and (b) shows a visualization of the Duval triangle method using the MATLAB application. The red dot in the image is the coordinates of the type of disturbance. The results of January 23, 2020 and August 14, 2020 are disturbances in the T1 zone. The T1 zone indicates that the transformer is experiencing a thermal fault (t<300 °C). Indications of thermal disturbance t<300 °C occur due to discharge caused by air trapped in the insulation system and overheating the conductor wire insulation.

Table 10. Test results from the Rogers ratio method

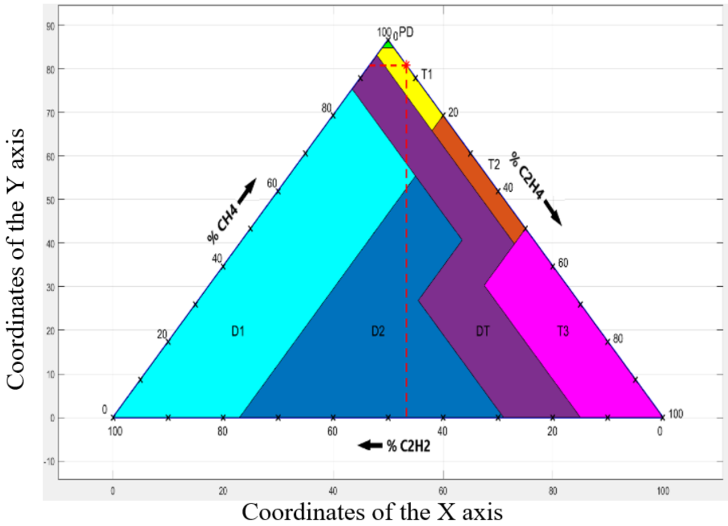
Gas	Jan 23, 2020 (%)	Aug 14, 2020 (%)
C_2H_2	0	0
C_2H_4	13.91	6.69
CH_4	86.08	93.30

4.5. Transformer failure evaluation based on basic gas method

The basic gas method calculation is almost the same as the Rogers ratio method. The difference between these two methods lies in the range of ratios used. The results of the gas analysis using the basic gas method based on Table 5 are shown in Table 11. The results obtained are in the samples of January 23, 2020 and August 14, 2020. The transformer is in the T1 zone, which indicates the transformer is experiencing thermal disturbances (t < 300 °C).



(a)



(b)

Figure 6. Coordinates of the Duval triangle disturbance in the (a) January 23, 2020 and (b) August 14, 2020

Table 11. Test results from the Rogers ratio method

Date	Failure Indication	R2 $\frac{C_2H_2}{C_2H_4}$	R1 $\frac{CH_4}{H_2}$	R5 $\frac{C_2H_4}{C_2H_6}$
Jan 23, 2020	T1 (t<300 °C)	0 (non- significant)	2.91176 (>1)	0.02116 (<1)
Aug 14, 2020	T1 (t<300 °C)	0 (non- significant)	39 (>1)	0.017699 (<1)

4.6. Transformer failure evaluation based on Duval pentagon method

After calculating (5)-(9), the results of the relative presence of each gas are obtained, as shown in Table 12. After obtaining the relative percentage of each gas, the coordinates of each gas are determined using (10) and (11), as shown in Table 13. Further, after obtaining the coordinates of each gas, the next step is to find the area of the point and the center point (centroid) of the combined points that form a pentagon based on (12)-(14), as shown in Table 14.

After obtaining the centroid value of each sample, the coordinates are visualized into three pentagon methods, namely Duval pentagon 1, Duval pentagon 2, and combine Duval pentagons, as shown in Figures 7(a) to (c). Based on calculations using the Duval pentagon method, the results of the centroid coordinates are C_x=-27.67 and C_y=6.57 [4]. The coordinates of the centroid are then visualized into the Duval pentagon. The results obtained are the three types of Duval pentagon used: Duval pentagon 1, Duval pentagon 2, and Combined Duval pentagon. It is found that the transformer experiences stray gassing in oil at temperatures of 120 °C and 200 °C. A stray gassing condition is where there are gases in the normal transformer operation. The presence of an S zone (stray gassing) increases the ability of the Duval pentagon method to determine the normal aging of transformer insulation, as seen in Figure 7.

Table 12. Test results from the Rogers ratio method

Gas	Jan 23 2020 (%)	Aug 14, 2020 (%)
(H_2)	3.75	0.49
(C_2H_6)	83.53	78.70
(CH_4)	10.93	19.40
(C_2H_4)	1.76	1.39
(C_2H_2)	0	0

Table 13. Gas point coordinates the pentagon Duval method

Gas	Jan 23, 2020 (x,y)	Aug 14, 2020 (x,y)
H_2	(0, 3.75)	(0, 0.49)
C_2H_6	(-79.44, 25.81)	(-74.85, 24.32)
CH_4	(-6.42, -8.85)	(-11.40, -15.69)
C_2H_4	(1.03, -1.43)	(0.81, -1.12)
C_2H_2	(0, 0)	(0, 0)

Table 14. DGA evaluation using the Duval pentagon method

Gas	Jan 23, 2020	Aug 14, 2020
A	592.98	757.55
C_x	-27.67	-28.23
C_y	6.57	2.86

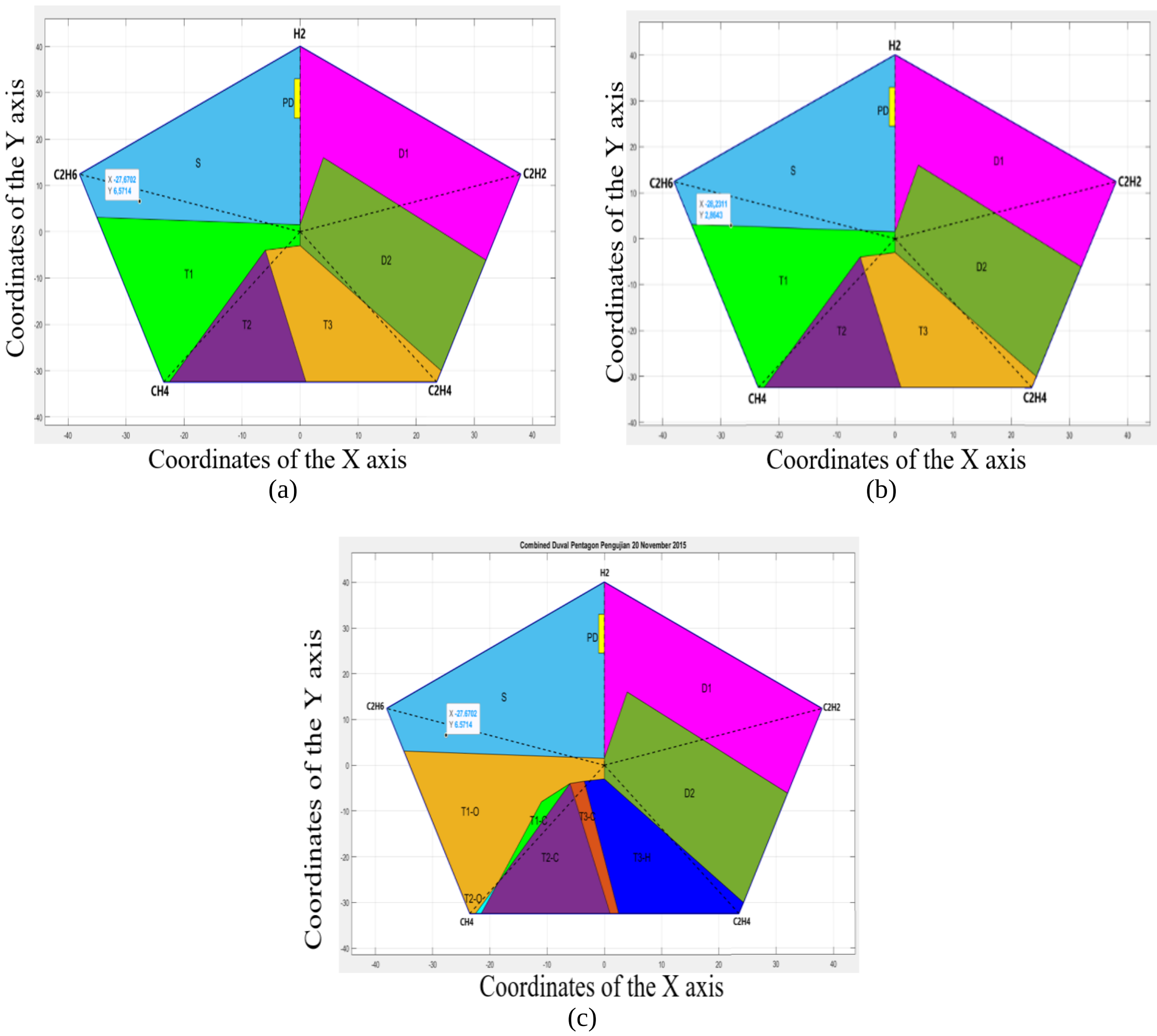
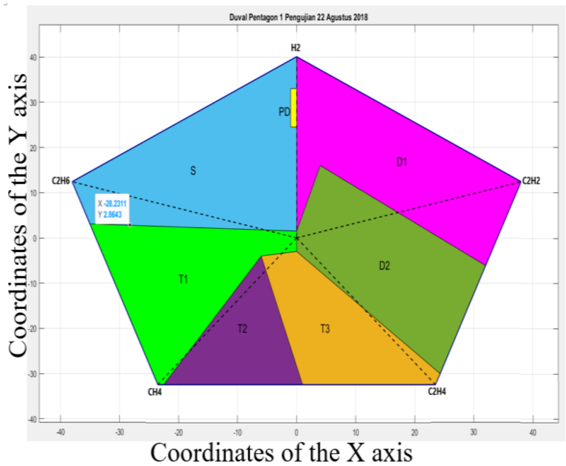
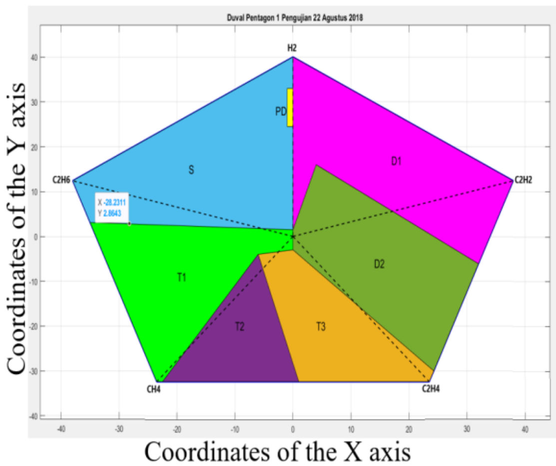


Figure 7. Testing on January 23, 2020 at (a) Duval pentagon 1, (b) Duval pentagon 2, and (c) combined Duval pentagons

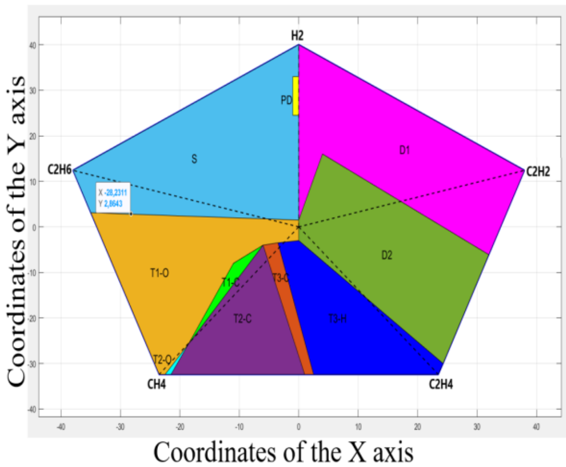
On the other hands, in Figures 8(a) to (c), the results of the centroid coordinates are C_x=-27.67 and C_y=6.57. The coordinates of the centroid are then visualized into the Duval pentagon. The results obtained are the three types of Duval pentagon used: Duval pentagon 1, Duval pentagon 2, and combined Duval pentagon. It is found that the transformer experiences stray gassing in oil at temperatures of 120 °C and 200 °C. A stray gassing condition is where there are gases in the normal transformer operation. The presence of an S zone (stray gassing) increases the ability of the Duval pentagon method to determine the normal aging of transformer insulation.



(a)



(b)



(c)

Figure 8. Testing on August 14, 2020 at (a) Duval pentagon 1, (b) Duval pentagon 2, and (c) combined Duval pentagons

5. CONCLUSION

The study's findings led to the following conclusions: The first, the TDCG method shows that gas levels such as C_2H_6 and CH_4 have exceeded the normal limit. According to the standard rate of gas evolution, the presence of CH_4 gas, which is already in condition 2, and C_2H_6, which is already in condition 4, indicates that the PPTR 1 transformer with serial number 80900075 in the electricity distribution section of PT Inalum has experienced a hot spot on the transformer at a temperature >200 °C. Following this result, the key gas method gives the results of a thermal cellulose diagnosis. The relative concentrations of the two main CO_2 and CO gases lead to the failure state of cellulose thermal insulation. The dominance of CO and CO_2 gases indicate the decomposition of PPTR 1 transformer insulation paper with serial number 80900075 due to the transformer insulating paper has become more heated. However, the Rogers ratio method cannot identify the disturbance that occurs, but the results are close to cases 4 and 5. Cases 4 and 5 in the roger ratio method are a condition of thermal failure caused by an increase in temperature. This has the disadvantage of the open method. It is a possibility that the results are outside the range specified by the standard. Furthermore, the

Duval triangle method provides a diagnosis of thermal fault results T1 (t<300 °C) on the samples of January 23, 2020 and August 14, 2020. This condition states that the PPTR 1 transformer with serial number 80900075 has a hot spot with a temperature range of 160 °C<t<300 °C. The visual indication in the T1 fault is that the transformer paper insulation changes color to brown at a temperature >200 °C. Meanwhile, the basic gas method gives the result of T1 disturbance, namely thermal disturbance with (t<300 °C). This condition states that the PPTR 1 transformer with serial number 80900075 has a hot spot with a temperature range of 160 °C<t<300 °C. Hot spots on the transformer can occur around the windings of the transformer. The visual indication in the T1 fault is that the transformer paper insulation changes color to brown at a temperature >200 °C. After that, tests using the Duval pentagon method showed that each sample of the transformer indicated stray gassing (120 °C<t<300 °C) in the oil. The stray gassing condition indicates that the PPTR 1 transformer with serial number 80900075 has a hot spot with a temperature range of 120 °C<t<300 °C. Then, The Duval pentagon method can identify faults better because this method uses five gas concentrations at once in the fault identification process so that it has more fault classifications and can identify normal aging in transformer oil. The last conclusion, after doing the DGA analysis with several methods described above, it was found that each DGA method stated that the transformer had an increase in temperature, which was above normal temperature. According to the findings of the examination of the techniques employed, after cutting the operational temperature range of the transformer into slices, it is found that the PPTR 1 transformer with serial number 80900075 in the electricity distribution section of PT. Inalum has a hot spot with a temperature range of 160 °C<t<200 °C. The transformer coil has the hotspot with the highest temperature, which is located between the coil and the iron core at the highest transformer load. The load and ambient temperature have an impact on the hot-spot temperature. An increase in ambient temperature, the way the transformer is loaded, and an insufficient cooling system can all cause the working temperature of the transformer to rise.

REFERENCES

[1] N. Bakar, A. Abu-Siada, and S. Islam, “A review of dissolved gas analysis measurement and interpretation techniques,” *IEEE Electrical Insulation Magazine*, vol. 30, no. 3, pp. 39–49, May 2014, doi: 10.1109/MEI.2014.6804740.

[2] H.-C. Sun, Y.-C. Huang, and C.-M. Huang, “A review of dissolved gas analysis in power transformers,” *Energy Procedia*, vol. 14, pp. 1220–1225, 2012, doi: 10.1016/j.egypro.2011.12.1079.

[3] H. Syafruddin and H. P. Nugroho, “Dissolved gas analysis (DGA) for diagnosis of fault in oil-immersed power transformers: a case study,” in *2020 4rd International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM)*, Sep. 2020, pp. 57–62, doi: 10.1109/ELTICOM50775.2020.9230491.

[4] N. Zope, S. I. Ali, S. Padmanaban, M. S. Bhaskar, and L. Mihet-Popa, “Analysis of 132kV/33kV 15MVA power transformer dissolved gas using transport-X Kelman Kit through Duval’s triangle and Roger’s ratio prediction,” in *2018 IEEE International Conference on Industrial Technology (ICIT)*, Feb. 2018, pp. 1160–1164, doi: 10.1109/ICIT.2018.8352342.

[5] J. Faiz and M. Soleimani, “Dissolved gas analysis evaluation in electric power transformers using conventional methods a review,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 2, pp. 1239–1248, Apr. 2017, doi: 10.1109/TDEI.2017.005959.

[6] T. B. Shanker, H. N. Nagamani, D. Antony, and G. S. Punekar, “Case studies on transformer fault diagnosis using dissolved gas analysis,” in *2017 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Nov. 2017, pp. 1–3, doi: 10.1109/APPEEC.2017.8309010.

[7] International Council of Large Electricity Systems. Study committee A2., *Guide for transformer maintenance*. CIGRÉ, 2011.

[8] “IEEE guide for the interpretation of gases generated in mineral oil-immersed transformers,” *IEEE Std C57.104-2019 (Revision of IEEE Std C57.104-2008)*, pp. 1–98, 2019, doi: 10.1109/IEEESTD.2019.8890040.

[9] IEC, “Mineral oil-filled electrical equipment in service–Guidance on the interpretation of dissolved and free gases analysis,” *International Electrotechnical Commission*, vol. 2003, 2015.

[10] "IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers," in *IEEE Std C57.104-1991*, 1992, doi: 10.1109/IEEESTD.1992.106973.

[11] R. W. Erickson and D. Maksimović, *Fundamentals of power electronics*. Cham: Springer International Publishing, 2020.

[12] M. Horning, J. J. Kelly, and S. Myers, *Transformer maintenance guide*. Transformer Maintenance Institute, 2001.

[13] E. Wannapring, C. Suwanasri, and T. Suwanasri, “Dissolved gas analysis methods for distribution transformers,” in *2016 13th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Jun. 2016, pp. 1–6, doi: 10.1109/ECTICon.2016.7561320.

[14] D. K. Shen and S. Gu, “The mechanism for thermal decomposition of cellulose and its main products,” *Bioresource Technology*, vol. 100, no. 24, pp. 6496–6504, Dec. 2009, doi: 10.1016/j.biortech.2009.06.095.

[15] Z. Luo *et al.*, “Dissolved gas analysis of insulating oil in electric power transformers: a case study using SDAE-LSTM,” *Mathematical Problems in Engineering*, vol. 2020, pp. 1–10, Nov. 2020, doi: 10.1155/2020/2420456.

[16] K. Bacha, S. Souahlia, and M. Gossa, “Power transformer fault diagnosis based on dissolved gas analysis by support vector machine,” *Electric Power Systems Research*, vol. 83, no. 1, pp. 73–79, Feb. 2012, doi: 10.1016/j.epsr.2011.09.012.

[17] A. Lakehal and F. Tachi, “Bayesian Duval triangle method for fault prediction and assessment of oil immersed transformers,” *Measurement and Control*, vol. 50, no. 4, pp. 103–109, May 2017, doi: 10.1177/0020294017707461.

[18] H.-C. Sun, Y.-C. Huang, and C.-M. Huang, “A review of dissolved gas analysis in power transformers,” *Energy Procedia*, vol. 14, pp. 1220–1225, 2012, doi: 10.1016/j.egypro.2011.12.1079.

[19] M. Duval and L. Lamarre, “The Duval pentagon-a new complementary tool for the interpretation of dissolved gas analysis in transformers,” *IEEE Electrical Insulation Magazine*, vol. 30, no. 6, pp. 9–12, Nov. 2014, doi: 10.1109/MEI.2014.6943428.

[20] N. Pattanadech and W. Wattakapaiboon, "Application of Duval pentagon compared with other DGA interpretation techniques: Case studies for actual transformer inspections including experience from power plants in Thailand," in *2019 5th International Conference on Engineering, Applied Sciences and Technology (ICEAST)*, Jul. 2019, pp. 1–4, doi: 10.1109/ICEAST.2019.8802523.
[21] L. Cheim, M. Duval, and S. Haider, "Combined Duval pentagons: a simplified approach," *Energies*, vol. 13, no. 11, Jun. 2020, doi: 10.3390/en13112859.
[22] A.-M. Aciu, C.-I. Nicola, M. Nicola, and M.-C. Nițu, "Complementary analysis for DGA based on duval methods and furan compounds using artificial neural networks," *Energies*, vol. 14, no. 3, Jan. 2021, doi: 10.3390/en14030588.
[23] IEC, "IEC 60599: Mineral oil-filled electrical equipment in service–Guidance on the interpretation of dissolved and free gases analysis," vol. 2003. International Electrotechnical Commission, 2015.
[24] W. Sikorski, K. Walczak, and P. Przybylek, "Moisture migration in an oil-paper insulation system in relation to online partial discharge monitoring of power transformers," *Energies*, vol. 9, no. 12, Dec. 2016, doi: 10.3390/en9121082.
[25] A. Teymouri and B. Vahidi, "Power transformer cellulosic insulation destruction assessment using a calculated index composed of CO, CO2, 2-Furfural, and Acetylene," *Cellulose*, vol. 28, no. 1, pp. 489–502, Jan. 2021, doi: 10.1007/s10570-020-03548-1.

BIOGRAPHIES OF AUTHORS

Yulianta Siregar was born July 09, 1978 in Medan, North Sumatera Utara, Indonesia. He did his undergraduate work at University of Sumatera Utara in Medan, North Sumatera Utara, Indonesia. He received a Bachelor of Engineering in 2004. After a while, he worked for a private company. He continued taking a master's program in Electrical Engineering at the Institute of Sepuluh Nopember, Surabaya, West Java, Indonesia, from 2007-2009. He was in a Ph.D. program at Kanazawa University, Japan, from 2016-2019. Until now, he lectured at Universitas Sumatera Utara. He can be contacted at email: julianta_srg@usu.ac.id.

Timothy Juan Hartanto Lumbanraja is a fresh graduate of Electrical Engineering bachelor's degree from Universitas Sumatera Utara in 2022. His research area field study is a high voltage, and electrical power system. He can be contacted at email: yopifernandopurba@gmail.com.