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Case Study and Comparison of High Voltage Power Transformer Dissolved Gas Analysis Assessed by Different Standards

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Abstract

A power transformer is a equipment that crucial in a power system. To prevent transformer failure, it is essential to rate the transformer condition, one of which is through the DGA test. IEC 60599 and IEEE C57.104 become guidance for transformer assessment through the DGA test. DGA is a method of determining transformer conditions and fault diagnosis by assessing transformer oil data samples. H2, CO2, C2H4, C2H2, C2H6, CH4, CO, O2, and N2 are among the dissolved gases measured to monitor transformer conditions. To determine the faults, the IRM, RRM, and DTM are used. The fault detected on 8 transformer case studies showed T1, T2, T3, PD, D1, and D2. Maintenance recommendations for 8 power transformers evaluated were presented.

Keywords : 150 kV Transformer, DGA, Fault Identification, IEEE C57,104-(2019), IEC 60599-(2015)
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1 Introduction

Various of voltage level delivered to electricity customer [1]. It generates by installing a power transformer in the electric power system. A transformer able to transform voltage levels by increase or decrease the applied voltage level without any change on frequency of the system by electromagnet induction via magnetic coupling without any direct connection [2], [3], [4]. Hence, power transformer had a crucial equipment in an electric power system and requiring proper maintenance to ensure its reliability and longevity of use [5], [6]. Transformer assessment using DGA (Dissolved Gas Analysis) method become one of maintenance process to prevent the transformer failure [7]. DGA method uses transformer oil insulation as a media for identifying fault occurred. The condition of transformer oil can serve as an indicator of transformer's performance [8], [9]. Generally, fault are classified into two types, namely electrical fault (PD, D1, and D2) and thermal fault (T1, T2, and T3). Fault arise in the transformer will cause the form of gas dissolved in the oil with relative nominal gas perform fault type occurred on transformer [10]. Type of gas dissolved such as methane (CH4), ethylene (C2H4), acetylene (C2H2), ethane (C2H6), carbon dioxide (CO2), carbon monoxide (CO), oxygen (O2), hydrogen (H2), and nitrogen (N2) [11]. Various methods have been utilized in numerous studies and research to examine the status of transformers, including the dissolved gas analysis (DGA)[12]. One such research project [13] focused on 150kV transformers and involved analyzing the oil's dielectric characteristics and dissolved gas content. The findings of this study revealed a hard correlation between coefficients parameter and the transformer's total operating time, which may impact its lifespan. Another study [14] not only assesses the condition of power transformers but also detects power disturbances using DGA data and a combination of Duval Methods, in line with the IEEE C57.104-(2019) guidelines. Additionally, other studies [15], [16], [17] discuss the identification of faults in transformer oil insulation through DGA analysis. One suggested method for diagnosing faults in transformers involves analyzing the condition of the oil using previous research [18]. Using DGA to follow the trend of dissolved gas in trasnformer oil, this method monitors real-time operational conditions [19]. To perform DGA, a sample of the oil must be taken and analyzed for gas data interpretation [20]. Analyzing DGA data based on gas concentration, the trend of average gas increase per year, and differences between the latest and previous tests. After analyzing the transformer oil's status, the faults can be identified [21]. Previous studies have commonly used methods such as the IRM (IEC Ratio Method), RRM (Roger's Ratio Method), DRM (Doernenburg Ratio Method), DTM (Duval Triangle Method), and DPM (Duval Pentagon Method) [14]. This case study will compare the interpretation result using two different standards, namely IEC 60599-(2015) and IEEE C57.104-(2019) to determine effectiveness in determining conditions in a transformer using DGA. The things that compared between two standards, it is parameter limits and the same method for identifying faults in insulating oil used to assess a transformer condition. The methods taken from the standards is the IRM, RRM, and DTM which use 5 type of gas to identify the fault occurred [22]. This case study will also discuss recommendation action based on the results of fault diagnosis according to the standards

2 Method

2.1 Collected Transformer Dissolved Gas Data

Dissolved gas data are collected from historical DGA test of 8 150 kV power transformer at PLN UIT JBM. DGA test is applied annual on 8 transformers. In this study, 5 hydrocarbon which use to identify the fault on transformers are H2, CH4, C2H2, C2H4, and C2H6. It should be containing the gas concentration, deltas, and rate of increase.

2.2 Workflow Research

To complete the case study, Figure 1 present the flowchart outlining the step to conduct this research. Step one involves conducting a literature study to find reference sources that are relevant to the problem. After sufficient reference sources are used as a reference, DGA data are collected. After all data is complete, DGA data analysis using two different standard is performed with gas concentration limits and rates gas increase. When the transformer oil in abnormal condition, determine the fault severity using IRM, RRM and DTM. Then determine recommended action based on the results of oil conditions and fault occur according to IEC and IEEE standards

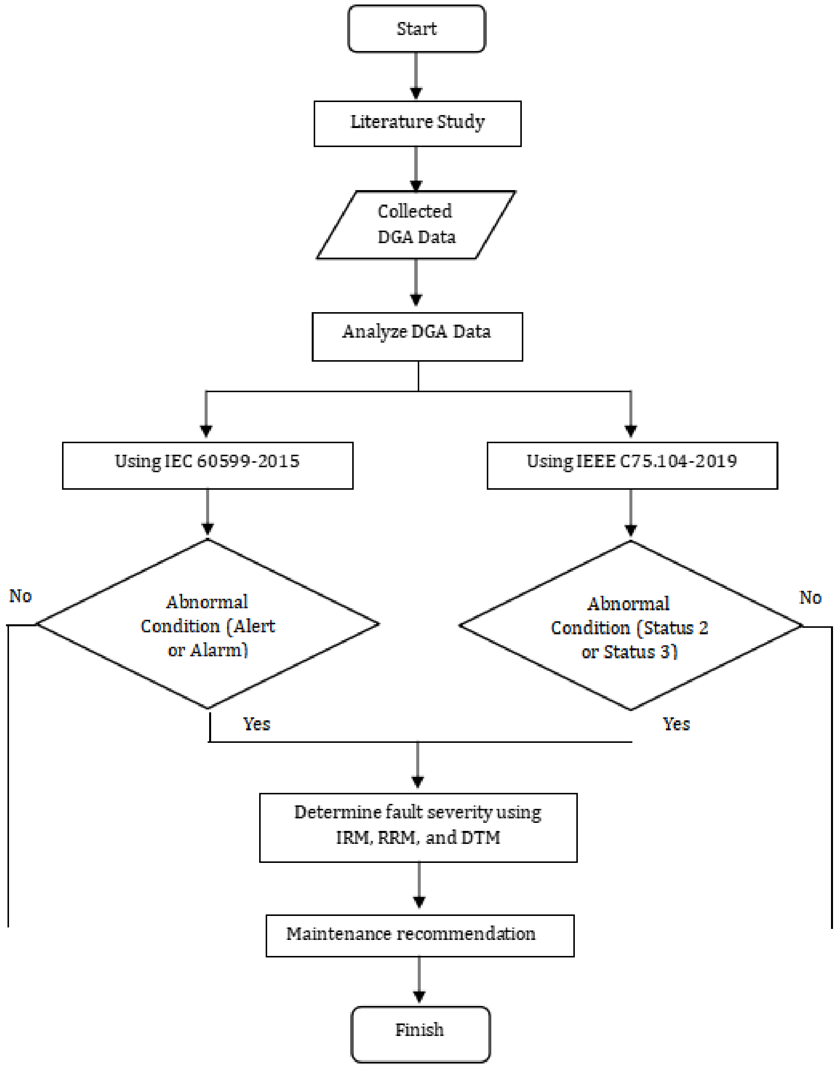

Figure 1: Flowchart of the study

2.3 Transformer Abnormality Condition

To determine the abnormal;ity of a transformer, one can examine the levels of dissolved gas and the rate of gas accumulation, which reveals the DGA status. The transformer oil condition can be evaluated using a method described in the IEC 60599 (2015).

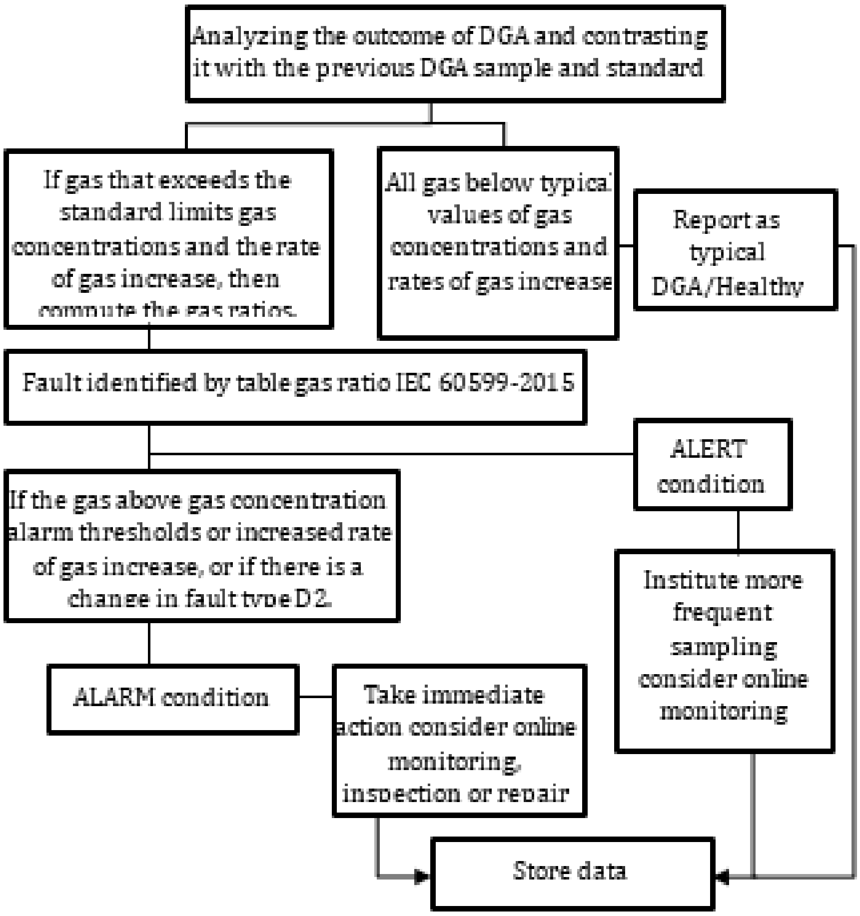

Figure 2: Flowchart IEC 60599-2015 [23]

Figure 2 illustrates the process for assessing the state of transformer oil, which can be classified into two conditions which are Normal and Fault. The Normal condition is distinguished by lower-than-usual amounts of dissolved gases and gas buildup rates that are within the expected range. During this phase, routine maintenance tests are performed according to a predefined timetable. The fault condition, on the other hand, is identified when one gas is thought to have exceeded the normal value, as indicated by the concentration of dissolved gas and the pace of gas accumulation.

Table 1: Limit of Dissolved Gas IEC 60599 (2015) [23]

Dissolved Gas	C_2H_2	H_2	CH_4	C_2H_4	C_2H_6	CO	CO_2
Concentrations ($\mu l/l$)	2-20	50-150	30-130	60-280	20-90	400-600	3800-14000
Rates of Gas Increase ($\mu l/l/year$)	0 - 4	35-132	10-120	32-146	5-90	260-1060	1700-10000

If there is one gas detected in the area of table 1 that is the limit of typical value dissolved gas, it is certain that the transformer condition in abnormal or fault condition and needs to be analyze for maintenance refer to the condition. Fault conditions in IEC 60599-2015 are divided into 2 types, there are ALERT and ALARM. The ALERT condition occurs when the DGA test result falls within the range specified in table 1 and there is no interference detected in D2 (High Energy Discharge). N this situation, it is necessary to increase the frequency of taking samples for maintenance purposes. For ALARM, the condition occurs when one of the values of the contained gas is above table 1 or is detected as a D2 disorder, and it is necessary to carry out maintenance actions based on online monitoring. In the IEEE C57.104-2019 have their own standard status and parameter of transformer health index. DGA testing flow by using IEEE C57.104-2019 can be look a the Figure 3.

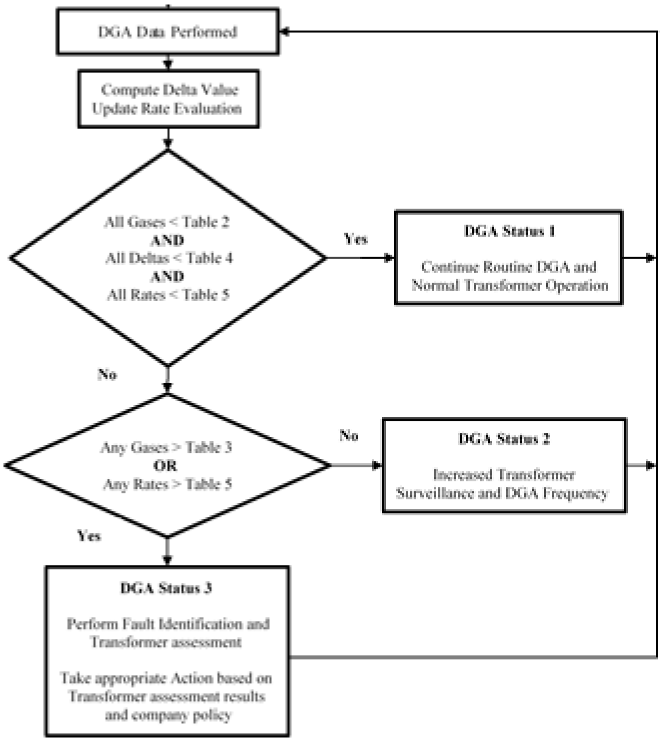

Figure 3: Flowchart of IEEE C57.104-2019[24]

The DGA test procedure, as outlined in IEEE C57.104-2019 and depicted in Figure 3, begins with initiating a routine DGA program to collect a sample. Subsequently, the DGA parameters are calculated and compared to the typical values specified in Table IEEE C57.104-2019. An analysis is then performed based on this comparison. If all gas numbers are less than (<) those in Table 2, all delta numbers are less than (<) those in Table 4, and all rates' numbers are less than (<) those in Table 5, the result is classified as DGA Status 1. If the parameters do not meet the requirements, the gas and rates of the DGA are further examined. If no gas type number exceeds (>) the values in Table 3 or no rates type number exceeds (>) the values in Table 5, the result is classified as DGA Status 2. If the parameters do not meet the requirements, the gas and rates of the DGA are further examined. If one gas type number exceeds (>) the values in Table 2 or one rates type number exceeds (>) the values in Table 4, the result is classified as DGA Status 3.

Table 2: Limit of typical value concentration IEEE C57.104 (2019) [24]

Dissolved Gas	$O2/N2 \leq 0.2$ Transformer Age (year)				$O2/N2 > 0.2$ Transformer Age (year)			
	Unknown	1-9	10-30	> 30	Unknown	1-9	10-30	> 30
H2	80	75		100	40		40	
CH4	90	45	90	110	20		20	
C2H6	90	30	90	150	15		15	
C2H4	50	20	50	90	50	25	60	
C2H2	1		1		2		2	
CO	900		900		500		500	
CO2	9000	5000	10000		5000	3500	5500	

Table 3: Maximal Limit of typical value concentration IEEE C57.104 (2019) [24]

Dissolved Gas	$O2/N2 \leq 0.2$ Transformer Age (year)				$O2/N2 > 0.2$ Transformer Age (year)			
	Unknown	1-9	10-30	> 30	Unknown	1-9	10-30	> 30
H2	200		200		90		90	
CH4	150	100	150	200	50	60		30
C2H6	175	70	175	250	40	30	40	
C2H4	100	40	95	175	100	80	125	
C2H2	2	2		4	7		7	
CO	1100		1100		600		600	
CO2	12500	7000	14000		7000	5000	8000	

Table 4: Limit of Delta Values IEEE C57.104 (2019) [24]

Gas	$O2/N2 \leq 0.2$	$O2/N2 > 0.2$
H2	40	25
CH4	30	10
C2H6	25	7
C2H4	20	
C2H2	> 0	
CO	250	175
CO2	2500	1750

Table 5: Limit of Rates Gas Increase IEEE C57.104 (2019) [24]

Dissolved Gas	$O2/N2 \leq 0.2$ 4-9 months	$O2/N2 > 0.2$ 10-24 months	4-9 months	10-24 months
H2	50	20	25	10
CH4	15	10	4	3
C2H6	15	9	3	2
C2H4	10	7	7	5
C2H2	Any increasing rate		Any increasing rate	
CO	200	100	100	80
CO2	1750	1000	1000	800

The concentrations of dissolved gas in the oil are shown in Tables 2 and 3. Table 2 reflects the population's 90th percentile DGA result, whereas Table 3 indicates the population's 95th percentile DGA result. Table 4 shows gas concentration values based on the 95th percentile of the differences between two different DGA values, without any time adjustments. This table helps determine if there is an unusual gas rise in the transformer. In such cases, it is recommended to take a confirmatory sample. Table 5 shows the 95th percentile rate calculated using multi-point linear regression, which eliminates variations introduced by the laboratory DGA analysis method. Table 5 is useful to detecting the possibility of active gassing based on a series of DGA results.

2.4 Identification Fault Method

There are several methods to identify the fault refers to IEC..60599-2015 and IEEE..C57.104-2019, namely IRM, RRM, and DTM. For IRM (Table 6) and RRM (Table 7) 5 gases are used, including methane, ethylene, acetylene, ethane, and hydrogen also three gas ratios are calculated, namely C2H2/C2H4, CH4/ H2, and C2H4/ C2H6. IRM table on Table 6 provide the standard limit for various fault such as partial..discharge (PD), low..discharge (D1), high..discharge (D2), thermal fault $< 300°C$ (T1), Thermal fault $300°C < t > 700°C$ (T2), and Thermal fault $> 700°C$ (T3). In this research for non-significant value limit in gas ratio used 0. One of the methods outlined in IEEE C57.104-2019 for detecting fault in transformer through DGA testing is the application of RRM as shown in Table 7. This method utilizes three gas ratios, namely CH4/H2, C2H4/C2H6, and C2H2/C2H4, to determine the fault occur on the transformer.

Table 6: Interpretation Gas Ratio of IEC 60599-2015[23]

Fault	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
PD	0 or >0	< 0.1	<0.2
D1	>1	0.1 - 0.5	>1
D2	0.6 - 2.5	0.1 -1	>2
T1	0 or >0	0 or >0	<1
T2	< 0.1	>1	1-4
T3	< 0.2	>1	>4

Table 7: Rogers Ratio Method in IEEE C57.014-2019[24]

C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Suggested fault diagnosis
< 0.1	0.1 to 1.0	< 0.1	Normal
< 0.1	< 0.1	< 0.1	PD - D1
0.1 to 3.0	0.1 to 1.0	0.1 to 3.0	D2
< 0.1	0.1 to 1.0	0.1 to 3.0	T1
< 0.1	> 0.1	0.1 to 3.0	T2
< 0.1	> 0.1	> 3.0	T3

Three gases from the DGA test parameters are used in the Duval Triangle approach, which is shown in Figure 4, to pinpoint the problem. Methane (CH4) is used to diagnose faults with low energy or temperature, ethylene (C2H4) to diagnose faults with high temperature, and acetylene (C2H2) to diagnose faults with extremely high temperature, high energy, or arcing faults. These three gases (CH4 + C2H4 + C2H2) have a combined concentration of 100%. To plot the percentages of these three gases, a triangle is drawn.

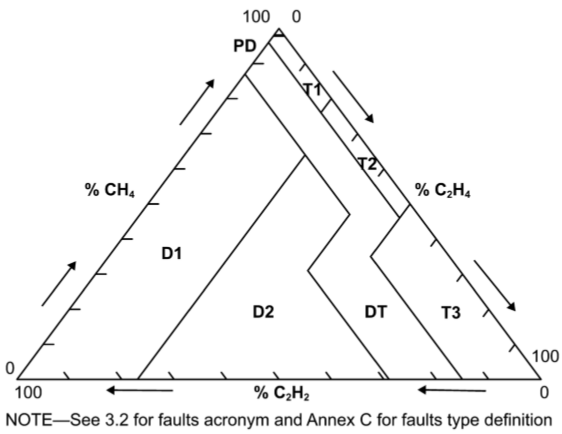

Figure 4: Duval Triangle Method[23][24]

The triangle plot exists for mapping the fault identification according to the three gas parameters. Each parameter concentration gives the fault diagnosis on the transformer. The percentages of each gas can be found with the following equation below:

$$\%CH4 = \frac{CH4}{(CH4 + C2H4 + C2H2}x100 \quad (1)$$

$$\%C2H4 = \frac{C2H4}{(CH4 + C2H4 + C2H2}x100 \quad (2)$$

$$\%C2H2 = \frac{C2H2}{(CH4 + C2H4 + C2H2}x100 \quad (3)$$

In IEC standards, the presence of CO2 and CO dissolved gases can serve as indicator to identify the fault occure in the paper insulation. If an error occurs and CO > 1000 ppm and the CO2/CO ratio is below 3, it may suggest interfence with carbonation in the paper. If CO2 more than (>) 10,000 ppm and the CO2/CO ratio more than (>) 10, it can indicate overheating of the paper ($> 160°C$) or oil oxidation. In the case of thermal stress on the paper at low temperatures ($< 160°C$) in a long time and high CO2/CO ratio in old transformers paper degradation may occur and it is recommended for further analysis using furan test. Dissolved gases O2 and N2 may come into contact with atmospheric air in conservators with rubber bags or due to leaks in sealed equipment. Under normal circumstances, the $O2/N2$ ratio is 0.5. If the ratio decreases during services, it can be assumed that oil oxidation and paper aging have occurred. In a closed system transformer and a ratio below 3 indicates excessive oxygen consumption.

2.5 Maintenance Recommendation

To ensure optimal transformer performance, regular maintenance procedures are required. Maintenance is widely recognized as the most crucial activity that ensures the operational reliability of industrial processes and equipment. The maintenance process should aim to reduce equipment intervention time and minimize system downtime. Table 8 outlines some maintenance recommendations based on IEC 60599-2015, while table 9 provides maintenance recommendations based on IEEE C57.104-2019 for various conditions.

Table 8: Maintenance Recommendation According to IEC 60599-(2015)

Status Condition	Recommendation Maintenance
Normal	Carrying out routine tests once every year
Alert	Frequently sampling consider online monitoring
Alarm	Removing transformer from service and take immediate action it is inspection or repair consider online monitoring

Table 9: Maintenance Recommendation Refer to IEEE..C57.104-(2019)

Condition	Recommendation Maintenance
DGA Status 1	Maintain regular operations and the yearly DGA test
DGA Status 2	Increasing the frequency of sampling DGA test and monitoring is required
DGA Status 3	Close monitoring is required, on-line dissolved gas monitoring needed

3 Results and Discussion

3.1 DGA Test Result

This case study was conducted on transformer oil utilizing dissolved gas analysis, with oil samples from transformers analyzed. DGA data was collected from 8 samples of 150kV power transformers.

Table 10: Gas Concentration DGA Result

Transformer No	Age	H2	CO	C2H4	C2H2	CO2	C2H6	CH4	O2	N2
1	4	22.326	103	80	0	223.6	13.25	118	0	0
2	29	78	692	7	5	5331	5	8	0	0
3	3	0	39	0	0	1098	32	0	0	0
4	14	46	55	416	0	459	204	224	2033	2051
5	5	21	226	2	0	2783	53	39	0	0
6	7	85	217	2	0	1326	55	43	0	0
7	9	0	179	4	0	2818	318	133	0	0
8	14	4	59	0	5	781	0	0	51739	250078

Table 11: Rates of Gas Increase DGA Result

Transformer No	H2	CO	C2H4	C2H2	CO2	C2H6	CH4
1	0	39.138	0	0	0	0	0
2	0	0	0	1	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	24	0	0	570	9	0
6	19	17	0	0	173	10	7
7	0	28	1	0	618	62	23
8	14	17	62	0.0397	326	51	30

Table 12: Deltas Result

Transformer No	H2	CO	C2H4	C2H2	CO2	C2H6	CH4
1	11.144	61.365	31.657	0	0	0	7102.599
2	50.25	512.42	2.61	5	2684.95	1.54	8
3	1.54	0	1.42	0	0	0	2.73
4	9.294	8.1339	56.994	0	0	27.7193	41.9539
5	0	201.572	2	0	1364.188	30.289	39
6	78.861	194.702	27	0	0	34.956	43
7	0	159.41	2.907	0	715.611	201.975	121.167
8	1.189	0	0	3.2791	0	0	0

Table 10 show the outcomes of measuring the concentration of dissolved gas in transformers along with their ages. This table is valuable for assess the condition of a transformer in accordance with IEEE C57.104-2019 standard. The data used in the table are obtained from DGA tests conducted on 8 transformers with a voltage of 150kV. In addition, Table 11 presents the average yearly increase in gas concentration, which is helpful in monitoring the increase of each gas over time. Table 12 examines the differences between the latest and previous tests and is utilized in IEEE C57.104-2019 standard to assess the transformer condition. Those three tables are essential parts for using the DGA method to assess a transformer's condition.

3.2 DGA Status Condition

Table 13: Compare DGA Status Condition

Transformer No	IEC 60599-2015	IEEE C57.104-2019
1	ALERT	DGA STATUS 3
2	ALARM	DGA STATUS 3
3	ALERT	DGA STATUS 3
4	ALARM	DGA STATUS 3
5	ALERT	DGA STATUS 2
6	ALERT	DGA STATUS 3
7	ALARM	DGA STATUS 3
8	ALERT	DGA STATUS 3

By referring to Table 13, the condition of eight transformer samples can be obsrved. The analysis outcomes of these transformers using each standard indicates differences. According to IEC transformers 1, 3, 6, and 8, in Alert condition status, which is activated due to the presence of a gas with a concentration or rate of increase that surpasses typical values. However, it can be determined that the disturbance causing this Alert status is not high discharges energy (D2) based on IEC ratio. Meanwhile, based on IEEE, all transformer got condition in DGA Status 3, indicating that there are dissolved gases exceeding the maximum typical value of rates gas increase. Transformers 3 and 6 have different states because the gas concentration exceeds the gas rise rate provided in Table 4 IEEE. As a result, this transformer is classed as DGA Status 3, specifically for C2H6. However, according to IEC, the concentration of C2H6 surpasses the average amount but remains below the typical value for the warning limit. The C2H2 gas limit in transformer 8 differs between IEC and IEEE. The concentration of C2H2 at IEC is greater than the normal value of gas concentration (>2), however at IEEE it exceeds the maximum typical value indicated in Table 3. Disagreements in the DGA analysis methodology and the limit parameters set in the IEC and IEEE are causing these changes in circumstances. For the condition of the paper between 8 transformers, it is still in good condition, but for transformer 2, due to the old transformer condition, it is necessary to pay attention for insulation paper condition. In addition, the condition of the oil and paper insulation must take into account a gas, such as C2H2, that is suspected of forming when the arcing occurs. For the O2/N2 ratio itself, all transformers are in normal condition except for transformer 2 where there is an indication of a leak in the transformer section. The resulting ratio is 0.9 which indicates a leak and needs further investigation.

3.3 Fault Diagnostics

To find out in more detail the condition of the transformers, it is necessary to identify the faults that occur in each of transformers. In this case, 3 methods can be used to analyze the condition of transformers that showed in Table 14.

Table 14: Compare DGA Status Condition

	Gas Ratio		IEC Ratio	Roger's Ratio	Duval Triangle	
Transformer No	C2H2/C2H4	CH4/H2	C2H4/C2H6	Method (IRM)	Method (RRM)	Method (DTM)
1	0	5.29	6.04	T3	T3	T2
2	0.714	0.103	1.4	Can't Identify	Can't Identify	D2
3	0	0	0	PD	PD	Can't Identify
4	0	4.86	2.04	T2	T2	T3
5	0	1.85	0.4	T1	Can't Identify	T1
6	0	0.51	0.04	T1	Unit Normal	T1
7	0	0	0.01	T1	PD	T1
8	0	0	0	PD	PD	D1

According to the Rogers Ratio Method, different fault diagnoses were detected for transformer 6 and 7. In the case of transformer 6, T1 ($< 300°C$) fault diagnosis is identified using IRM. However, according to RRM, the transformer is considered to be in good condition for the oil and paper insulation. For transformer 7, IRM identify as T1 fault diagnosis, but RRM identified as PD (Partial Discharge) fault diagnosis. The transformer that can't identify the fault occur using IRM and RRM are typically due to not meeting the required parameter limits. Duval Triangle Method (DTM) is use to be other fault identification method for detecting the disturbances occurred. IEEE C56.104-2019 provides several types of DTM, including Duval Triangles 1, 4, and 5. However, to compare the both standards, DTM 1 are used to identify the disturbances that occur and contain gas concentrations of CH4, C2H2, and C2H4. Based on the identification results of the DTM in Transformer 4, a High Thermal Temperature Fault was detected, with a temperature greater than $700°C$. In Transformer 1, it was identified as a Thermal Temperature Fault with a temperature range between $700°C$ and $300°C$. In Transformers 6 and 7, it was identified as a Low Thermal Temperature Fault with a temperature below $300°C$. On the other hand, in Transformer 2, a High Discharge Energy (D2) disturbance was detected, and Transformer 8 detected as Low Energy Discharges (D1) disturbance. In transformer 3 there is no produced gas concentrations of CH4, C2H2, and C2H4 for DTM calculation. So, DTM cannot be performed.

3.4 Maintenance Recommendation

According to the results of the analysis of DGA test on 8 of 150kV power transformers, it is possible to know the status of the transformer and the disturbances that occur by taking a sample of transformer oil. Maintenance recommendation can be given according to the results and IEC 60599-2015 standard of the status of the transformer oil. According to the analysis result, maintenance recommendations on transformers 1, 5, and 6 are given decrease the load for reduce the heat and frequent sampling with online monitoring. On transformer 3 and 6 need some complementary test (electrical and acoustic) and increase sampling DGA test. For alarm conditions in transformers 2, 4, and 7 need to remove the transformer from service to do an inspection. In transformer 2 because the ratio $O2/N2$ is 0.9 and transformer is too old, so need to change the transformer for efficiency distribution service. Meanwhile, refers to IEEE C57.104-2019 for transformer 2 condition is increase the frequency of sampling DGA test and monitored the growth of DGA data. For DGA Status 3 which is in the transformer 1, 3, 4, 5, 6, 7, and 8 are need take action based on transformer expert or company policy.

4 Conclusion

The study compared IEC 60599-(2015) and IEEE C57.104-(2019) standards in assessing the condition of transformers through eight sample tests. The study conducted DGA testing on 150 kV power transformers and found discrepancies between the two standards. IEC 60599-2015 uses two components, gas concentration and gas rates increment, to determine transformer oil condition and can detect disturbances in transformers during Alert and Alarm conditions. On the other hand, IEEE C57.104-2019 uses three components, gas concentration, rates of gas increase, and deltas value, and has different limits in the $O2/N2$ ratio and transformer life [25]. Based on the analysis result the age transformer $>$ 10 years is need to extra monitor because quality oil transformer is decrease and it caused the growth of dissolved gas. From the result, fault identification using DTM is found to be more effective compare to the IRM and RRM. Additionally, combining the DGA data with other methods result more accurate yield in diagnosing faults.

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