Dissolved Gas Analysis of Generator Step Up Transformer in Grati Power Plant Using Random Forest Based Method

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Abstract— **Transformers are one of the important electrical equipment in the power system. To prevent some electrical contact on the component in transformers, an insulator or dielectric material is needed likely insulating oil. DGA test is important for diagnosis and deciding the maintenance of transformers. Duval Triangle and Duval Pentagon methods are DGA identification methods with the highest of accuracy compared to other methods. The data used in this article is from the DGA measurement test of transformers GT 3.1 Steam and Gas Power Plant Grati. The DGA data was analyzed by Random Forest based-model of Duval Triangle and Pentagon method, in accordance to IEEE C57.104-2019 and IEC 60599-2015 guidelines. Random Forest based-model has the best performance in implemented Duval method than others. The result of DGA identification using Random Forest based-model showed PD and S for Duval Triangle, and S for Duval Pentagon and from the results of identification using the Duval Triangle and Pentagon it does not always show the same results on the same test sample, so it is necessary to identify the history of DGA testing to get accurate results. This article presents the use of the combined Duval Triangle and Pentagon for diagnosis transformers.**

Keywords— Transformers, Dissolved Gas Analysis, Duval Triangle Method, Duval Pentagon Method, Random Forest.

I. INTRODUCTION

A transformer is one of the important electrical equipment in the power system that can function to transfer power from one voltage level to another voltage level [1]. To prevent the existence of several electrical contacts on the components in the transformer, an insulator or dielectric material is needed, namely insulating oil [2].

Insulating oil is able to prevent abnormal conditions such as leakage currents and high temperatures, due to its ability to act as both insulation and coolant. The main function of transformer oil is as an insulator that provides insulation between windings and as a transformer cooling medium [3][4]. Several conditions such as overload, overheat, and conditions due to loading can cause dissolved gas in the insulating oil. The appearance of dissolved gas in insulating oil can be used as an interpretation of the condition of the transformer.

One of the most efficient monitoring techniques for oil-immersed transformers is dissolved gas analysis (DGA). Dissolved gas testing or so-called DGA (Dissolved Gas Analysis) testing is a preventive maintenance carried out to analyze and monitor the condition of the transformer through the gas content of insulating oil [5]. It offers useful details regarding the state of the transformer's oil and paper insulation and aids in identifying the types of impending faults. DGA is now widely recognized as a reliable method for finding transformer defects before they become serious. In detecting disturbances through the results of the DGA test, there are several methods can be used. Such as the IEC ratio, doernenburg ratio, key gas, roger ratio, Duval Triangle, and Duval Pentagon. Almost all methods use the ratios method, except Duval Triangle and Duval Pentagon graphical method. This method is based on the area of the graphical. The advantage of this method is that it can detect disturbances using more than one hydrocarbon gas content with results covering many types of disturbances and has the highest level of accuracy compared to other DGA interpretation methods [6]. The results of this DGA interpretation method are used by utilities in determining appropriate maintenance actions on a transformer [7][8].

Several studies have been carried out using the Duval Triangle and Pentagon methods in interpreting transformer conditions, in reference [9] using the Duval Triangle method in examining the conditions of the Kamojang UPJP transformer. Then in [10] developing an Artificial Neural Network (ANN) model based on Duval Pentagon method in improving diagnostic and monitoring capabilities of transformers. And in reference [11] developed a fuzzy model and ANN based on Duval Triangle 1 to increase the accuracy of DGA interpretation. In reference [12], Random Forest models were developed to identify faults in power transformers, resulting in high accuracy compared to other machine learning algorithms.

In the IEEE C56.104-2019 standard [13] the Duval Triangle and Duval Pentagon methods may be used together on the same test sample to obtain accurate information. In this study, the dissolved gas analysis was carried out using both methods, namely the Duval Triangle and the Duval

Pentagon simultaneously, implementing the Random Forest model previously proposed in [12]. Using data from the DGA test results of the GT 3.1 PLTGU Grati transformer with a testing time range of July 2019-January 2021.

The most accurate method for identifying natural esters liquids is the Duval Triangle. The Duval Triangle diagnostic technique is used to identify oil-insulated high-voltage equipment, primarily transformers. It is based on the utilization of three hydrocarbon gases—CH4, C2H4, and C2H2—corresponding to the rising energy levels of gas creation in operational transformers. By visualizing the position of the dissolved gases on the Triangle map, the Duval approach allows for fault identification. [14]

The three main types of faults that may often be detected are Partial discharges (PD), electrical faults with high and low energy arcing (D1, D2), and hot spots with a variety of temperatures (T1, T2, T3) (thermal fault). Six zones of individual faults will be used to establish these fault types. Careless application of the Duval Triangle will lead to the identification of either one of the aforementioned problems because no region is indicated for normal aging conditions. Before using the Duval Triangle to interpret dissolved gases, it is best to first determine whether they are normal. Triangular coordinates are used to express the Triangle's three sides, which indicate the proportional quantities of CH4, C2H4, and C2H2 from 0 to 100 for each gas. Utilizing accumulated gas or the total rise between conjugated samples are two techniques that can be used with the Duval Triangle approach. The outcomes of both processes ought to be same. [14]

The Duval Pentagons were introduced more recently. It is a new graphical method for power transformer failure diagnostics (PTFD). The five hydrocarbon gases (H2, C2H2, C2H4, CH4, and C2H6) are used in the Pentagons, and they are arranged at their summits in a specific, clockwise order. [15]

The various fault types that the Pentagons and Triangles can detect are listed in Table 1. Basic flaws associated with Duval Triangle 1 and Duval Pentagon 1 are the first six faults. Using Duval Triangles 4 and 5, as well as Duval Pentagon 2, it is possible to identify the following four categories of thermal faults. [15]

TABLE I
FAULT TYPES [15]

Fault Types	
PD:	Partial Discharges (Corona)
D1:	Discharges of Low Energy (including Spark type)
D2:	Discharges of High Energy
T3:	Thermal Fault > 700°C
T2:	Thermal Fault 300°C to 700°C
T1:	Thermal Fault < 300°C
S-120 and S-200	Stray Gassing of Oil at 120°C and 200°C
O:	Overheating (< 250°C)
T3-H:	Thermal Fault T3 or T2 in Oil only
C:	Possible Carbonization of Paper

II. METHOD

A. DGA Status and TDCG (Total Dissolved Combustible Gas)

Checking the DGA status is useful for determining whether a transformer is normal, as seen from the amount of dissolved gas concentration in the insulating oil. Based on the magnitude of the status, the transformer can be increased in test intervals, changed oil, or operated normally [13][16].

TABLE II
STATUS DGA IEEE C57.104-2019

Status	Gas Concentrations Limit (ppm)						
	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
1	<80	<90	<1	<50	<90	<900	<9000
2	80-200	90-150	1-2	50-100	90-175	900-1100	9000-12500
3	>200	>150	>2	>100	>175	>1100	>12500

1) DGA Status 1

At low gas levels, in this condition the transformer can be operated normally. Preventive maintenance activities are still carried out routinely according to the schedule that has been made.

2) DGA Status 2

The medium gas level needs to increase transformer supervision and frequency of DGA testing. Transformers with DGA status 2 is considered suspicious for disturbances so additional investigations are required in the form of diagnosis or identification of faults using existing methods.

3) DGA State 3

If the gas level is high, it is necessary to identify faults and evaluate the transformer so that immediate action can be taken based on this assessment. Supervision of transformers should be increased and added testing of transformers. It is also advisable to consult with transformer manufacturers or transformer experts. If the results of the analysis of condition 3 are considered acceptable for the transformer to be put back into operation, then it is advisable to maintain typical monitoring of the DGA status.

TABLE III
GAS CONCENTRATIONS LIMIT IEC 60599-2015

Gas Concentrations (ppm)						
H2	CH4	C2H2	C2H4	C2H6	CO	CO2
50-150	30-130	-	60-280	20-90	400-600	3800-14000

If there is a gas content above table 3, it is necessary to carry out a disturbance analysis and maintenance based on the results of the analysis. There are two conditions from the results of the analysis, namely ALARM and ALERT conditions. An ALARM condition appears when the gas concentration reaches D2 (High energy discharge) according to the IEC Ratio and it is necessary to take immediate action based on on-line monitoring. The ALERT condition appears when the gas concentration exceeds table 2 but the results of the analysis are not D2 from the IEC Ratio, increased sampling needs to be done in this condition [16].

TABLE IV
IEC RATIO FAULT IDENTIFICATION

Case	C2H2/C2H4	CH4/H2	C2H4/C2H6
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

Table 4 shows the IEC ratio which indicated of faults from the combination of 3 ratios that is C2H2/C2H4, CH4/H2, and C2H4/C2H6.

B. Interpretation of CO and CO2 Gases

CO and CO2 gases are gases that are often formed due to the degradation of paper insulation and are easily formed due to the high temperature rise of the transformer. Table 5 is the limit of the CO2/CO ratio, based on IEC 60599 2015 and IEEE C57.104 2019 a CO2/CO ratio below 3 may indicate interference due to paper insulation. Meanwhile, a high CO2/CO ratio above 10 has the possibility of paper insulation experiencing excessive heating or oxidation of insulating oil [13][16].

TABLE V
CO2/CO RATIO [13][16]

CO2/CO Ratio IEC 60599-2015	CO2/CO Ratio IEEE Std C57.104-2019	Description
<3	<3	Fault
3-10	3-20	Normal
>10	>20	Fault

Table 5 shows the range and limit for CO2/CO ratio in faults conditions and normal conditions based on IEC 60599-2015 and IEEE C57.104-2019.

The flowchart of CO and CO2 interpretation is shown in Fig. 1. The First step is to prepare the DGA data, and check the concentration of CO and CO2. If the concentration of CO is less than 350 ppm or CO2 is less than 2500 ppm then the transformers is in normal condition, but if not check CO2/CO ratio. If CO2/CO ratio is more than 3 then transformers should be analyzed further for High concentrations of CO and CO2. If CO2/CO ratio is less than 3 and hydrocarbon formation is indicated then the DGA data should be analyzed with Duval Triangle or Duval Pentagon, if not there would be an indication of Oxidation in insulating oil.

In some cases, the CO2/CO ratio indicates disturbance but is not accompanied by high CO and CO2 gases. The involvement of paper insulation in disturbances needs to be confirmed by the emergence of other gas formations such as hydrocarbon gases so it is necessary to use methods such as the Duval Triangle and Duval Pentagon to get further analysis. Measurement of furan compounds is recommended when there is a suspicion of excessive paper degradation.

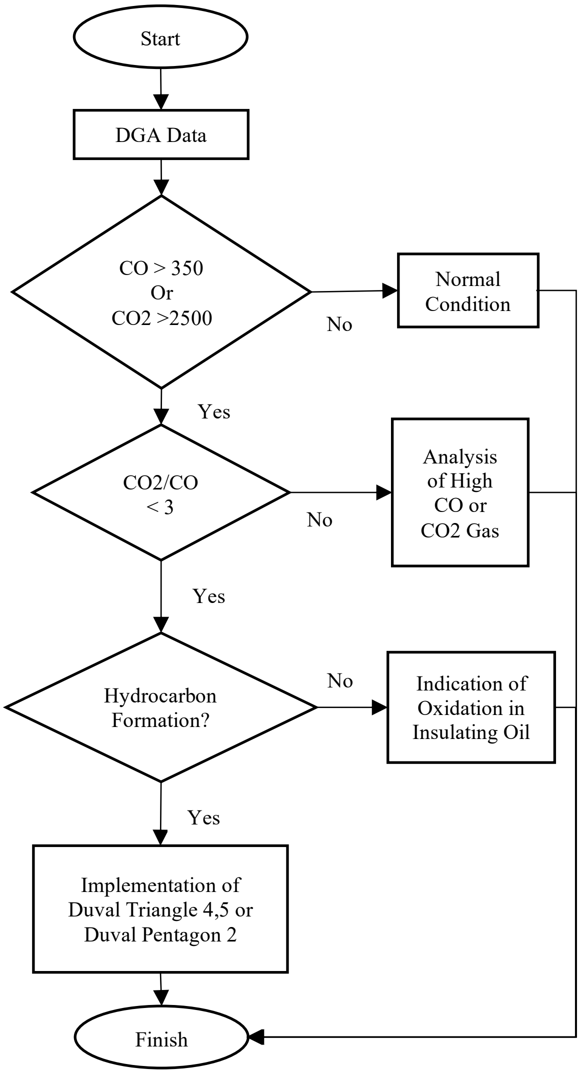

Figure 1. CO and CO2 Interpretation Flowchart [13]

C. Duval Triangle

Found by Dr. Michel Duval, the Duval Triangle method uses three hydrocarbon gases from the DGA test results. There are five types of Duval Triangle, there are Duval Triangle 1, 2, 3, 4, and 5. Analysis of mineral insulating oil uses Duval 1, 4, and 5 methods. Only if the µL/L (ppm v/v) measurements are accurate and dependable enough can all fault identification techniques on Duval Triangles 1-4-5 be applied.

1) Duval Triangle 1

Duval Triangle 1 uses methane (CH4), ethylene (C2H4), and acetylene (C2H2) gases. The relative percentages of these three gases are plotted on each side of the Triangle.

The total concentration of these three gases (CH4 + C2H4 + C2H2) is 100%. Changes in the conditions of the three gases will indicate failure conditions in the transformer [6].

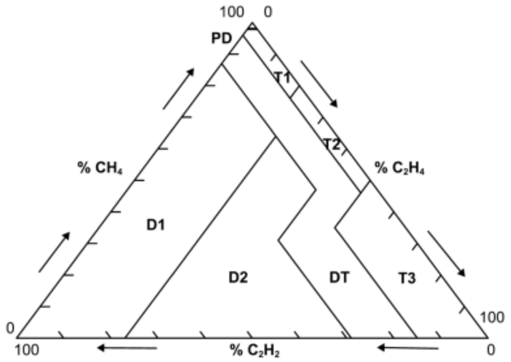

Figure 2. Duval Triangle 1 [13]

The advantages of the Duval Triangle 1 Method [13] include the ability to visually and quickly follow the evolution of faults with respect to time in a transformer, the fact that it always proposes a fault identification (it is a "closed" system as opposed to 2-gas ratios methods), and the fact that it is based on a large number of inspected cases of defective transformers in service. On the other hand, because it always provides a diagnostic, it should only be used to pinpoint a problem when other data suggests that it is likely to exist. The identification of a potential fault category does not prove that a fault actually exists.

2) Duval Triangle 4

Duval Triangle 4 uses methane (CH4), ethane (C2H6), and hydrogen (H2) gases. The total concentration of these three gases (CH4 + C2H6 + H2) is 100%. If the Duval Triangle analysis 1 is obtained PD, T1, or T2. More information can be obtained with the Duval Triangle 4 methods with the same DGA value [13].

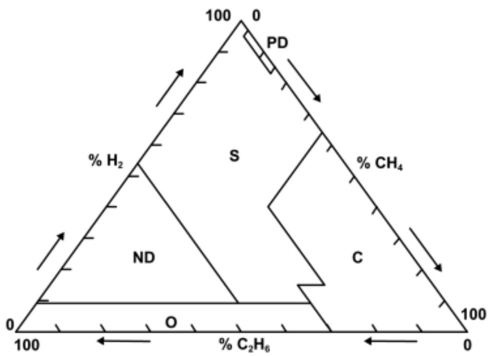

Figure 3. Duval Triangle 4 [13]

3) Duval Triangle 5

Duval Triangle 5 uses methane (CH4), ethane (C2H6), and acetylene (C2H4) gases. The total concentration of these three gases (CH4 + C2H4 + C2H6) is 100%. If the Duval Triangle analysis 1 obtained T2 or T3. More information can be obtained with the Duval Triangle 5 methods with the same DGA value [13]. A user can discern between high temperature faults T3/T2 in mineral oil only, which are less risky in transformers, and potentially more serious faults C including potential carbonization of paper using the Triangle 5 approach.

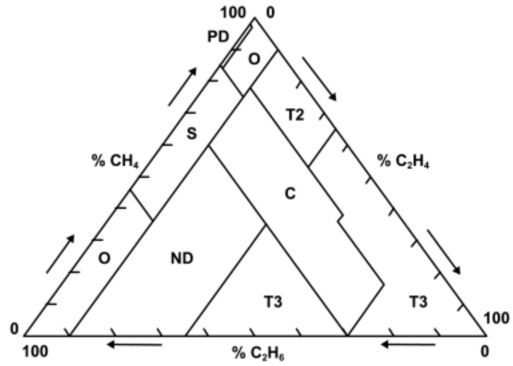

Figure 4. Duval Triangle 5 [13]

D. Duval Pentagon

At Duval Pentagon the relative percentages of the five major hydrocarbon gases (H2, CH4, C2H6, C2H4, C2H2) that have been analyzed by DGA were calculated [17]. The five hydrocarbon gases are used in the Pentagons, which are arranged at their tops in a specific, clockwise arrangement. Since CO and CO2 could be caused by a variety of other factors besides defects and would likely cause more confusion than clarity, they are not included.

$$H_2 = \frac{H_2}{H_2+CH_4+C_2H_2+C_2H_4+C_2H_6} \quad (1)$$

$$C_2H_6 = \frac{C_2H_6}{H_2+CH_4+C_2H_2+C_2H_4+C_2H_6} \quad (2)$$

$$CH_4 = \frac{CH_4}{H_2+CH_4+C_2H_2+C_2H_4+C_2H_6} \quad (3)$$

$$C_2H_2 = \frac{C_2H_2}{H_2+CH_4+C_2H_2+C_2H_4+C_2H_6} \quad (4)$$

$$C_2H_4 = \frac{C_2H_4}{H_2+CH_4+C_2H_2+C_2H_4+C_2H_6} \quad (5)$$

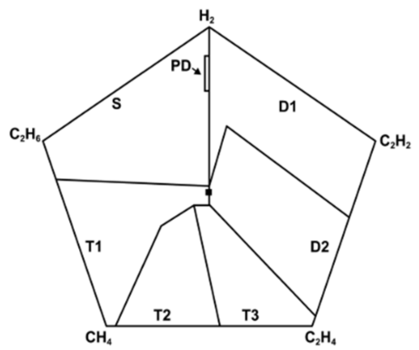

Figure 5. Duval Pentagon 1 method [13]

Duval Pentagon 1 has been shown to contain three thermal faults (T1, T2, and T3). Fig. 6 shows the Duval Pentagon 2 approach in action. As with Duval Pentagon 1, the Pentagon 2 approach enables the detection of the 3 fundamental electrical fault types (PD, D1 and D2) as well as further differentiation between the 4 additional sub-types of thermal faults of D.2 (S, O, C and T3 in mineral oil only). Faults T3 in mineral oil exclusively are identified in Duval Pentagon 2 as T3-H, where H stands for "Huile" or "oil" in French.

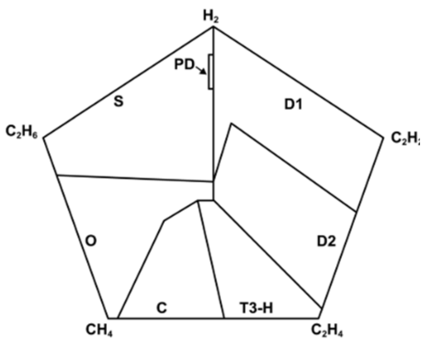

Figure 6. Duval Pentagon 2 method [13]

To calculate centroid coordinates, the (xi,yi) coordinates for each of the five points are calculated.

$$x_i = x \cos\alpha \quad (6)$$

$$y_i = y \sin\alpha \quad (7)$$

The centroid coordinates of the five points are calculated using the equation.

$$C_x = \frac{1}{6A}\sum_{i=0}^{n-1}(x_i + x_{i-1})(x_i y_{i-1} + x_{i-1} y_i) \quad (8)$$

$$C_y = \frac{1}{6A}\sum_{i=0}^{n-1}(y_i + y_{i-1})(x_i y_{i-1} + x_{i-1} y_i) \quad (9)$$

The xi and yi is the coordinates of the five points, Cx and Cy (x,y) are the centroid coordinates, and A is the surface of the polygon:

$$A = \frac{1}{2}\sum_{i=0}^{n-1}(x_i y_{i-1} - x_{i-1} y_i) \quad (10)$$

E. Random Forest based Fault Identification

In several publications, the use of ML to aid in power transformer condition assessment has been reported. The previous study has compared and evaluated the use of various algorithms to support fault identification in power transformers. The results in [12] show that Random Forest performed the best compared to the others. Therefore, this study implemented the Random Forest-model of Duval Methods previously proposed in [12]. The input dissolved gas data concentrations are classified into fault types as shown in Fig. 7.

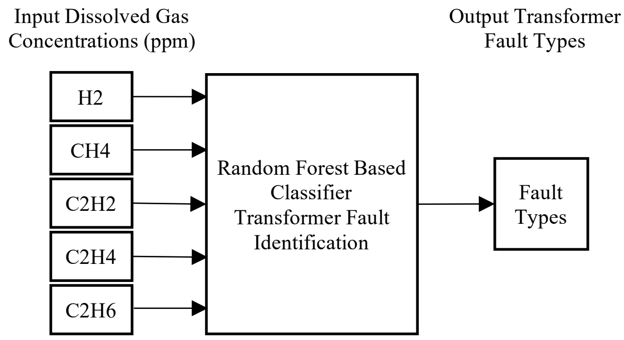

Figure 7. Random Forest Based Classifier proposed in [12]

III. RESULT AND DISCUSSION

A. Results of Checking DGA Status and Calculation of TDCG (Total Dissolved Combustible Gas)

Calculation of TDCG is used as a determination of the conditions for maintenance.

TABLE VI
GAS CONCENTRATIONS GT 3.1

Date	H2	CH4	C2H2	C2H4	C2H6	CO	TDCG
July 2019	17	2	0	0	0	272	291
September 2019	19	2	0	0	0	289	310
November 2019	0	0	0	0	0	205	205
January 2020	15	2	0	0	0	314	331
March 2020	0	0	0	0	0	332	332
May 2020	0	0	0	0	0	316	316
January 2021	17	4	0	0	2	454	477

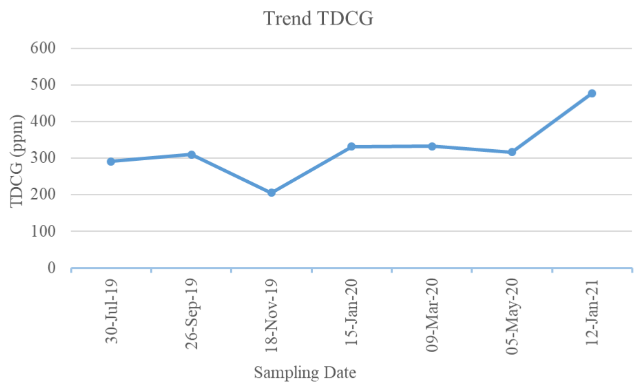

Figure 8. TDCG Data Trending

TDCG in the sample showed an increase after having a decrease on November 18 2019. Further monitoring is needed to facilitate analysis.

Determine transformer operating conditions and sampling intervals through TDCG results and TDCG increase per day based on the table in the IEEE C57.104 standard.

TABLE VII
SAMPLING CONDITIONS AND INTERVALS

Date	TDCG (ppm)	Condition	TDCG rate (ppm/day)	Sampling Intervals
30/07/2019	291	Cond 1	-	-
26/09/2019	310	Cond 1	0,327	Annual
18/11/2019	205	Cond 1	-1,981	Annual
15/01/2020	331	Cond 1	2,172	Annual
09/03/2020	332	Cond 1	0,018	Annual
05/05/2020	316	Cond 1	-0,280	Annual
12/01/2021	477	Cond 1	0,638	Annual

The value of the DGA test results is checked for DGA status using the IEEE C57.104-2019 and IEC 60599-2015 standards.

TABLE VIII
TRANSFORMER GT 3.1 DGA STATUS

Dissolved Gas Concentration (ppm)							DGA Status	
H2	CH4	C2H2	C2H4	C2H6	CO	CO2	IEEE	IEC
17	2	0	0	0	272	882	1	Healthy
19	2	0	0	0	289	901	1	Healthy
0	0	0	0	0	205	873	1	Healthy
15	2	0	0	0	314	1050	1	Healthy
0	0	0	0	0	332	1008	1	Healthy
0	0	0	0	0	316	934	1	Healthy
17	4	0	0	2	454	976	1	ALERT

Based on IEEE C57.104-2019 the DGA status of the GT 3.1 transformer is classified as status 1 which is allowed to operate normally without the need to increase the frequency of DGA testing. Whereas on January 12, 2021 the DGA status was not classified as "Healthy" because the CO value was above 400 ppm, so it needed to be identified through the IEC Ratio whether it was classified as D2 (high energy discharge) or not.

C2H2/C2H4 = 0/0 = 0 (assumed to be 0)
CH4/H2 = 4/17 = 0.23
C2H4/C2H6 = 0/2 = 0

Based on these three ratios, the identification of the IEC ratio was not detected as D2 (high energy discharge) so the status on January 12, 2021 was included as "ALERT".

B. CO and CO2 Gas Interpretation

In determining the normal level of dissolved gas, PLTGU Grati uses threshold values based on IEEE C57 104-2019 and IEC 60599-2015 standards.

TABLE IX
CO AND CO2 GAS INTERPRETATION RESULT

Date	CO (ppm)	CO2 (ppm)	CO2/CO
30/07/2019	272	882	3,24265
26/09/2019	289	901	3,11765
18/11/2019	205	873	4,25854
15/01/2020	314	1050	3,34395
09/03/2020	332	1008	3,03614
05/05/2020	316	934	2,9557
12/01/2021	454	976	2,14978

Based on the interpretation of CO and CO gases by looking at hydrocarbon formations, there is a possibility of abnormalities in paper insulation on January 12, 2021, so it was determined to apply Duval Triangle 4, 5 and Duval Pentagon 2 only to the DGA test sample on January 12, 2021.

C. Application of Duval Triangle

The DGA test results of the GT 3.1 transformer will be analyzed using the Duval Triangle 1 method, especially those containing CH4, C2H2, and C2H4 because the input parameters of Duval Triangle 1 are 3 gas concentrations, so if the 3 gas contents are absent then the transformer is considered normal on Duval Triangle identification 1.

After that from the interpretation of CO and CO2 gases, only Duval Triangles 4 and 5 were used in the test sample on January 12, 2021.

TABLE X
RESULT OF DUVAL TRIANGLE IDENTIFICATION

Date	DTM1	DTM4	DTM5	Conclusion
July 2019	PD	Not used	Not used	Indicated Partial Discharge
September 2019	PD	Not used	Not used	Indicated Partial Discharge
November 2019	Not used	Not used	Not used	No Indicated Faults
January 2020	PD	Not used	Not used	Indicated Partial Discharge
March 2020	Not used	Not used	Not used	No Indicated Faults
May 2020	Not used	Not used	Not used	No Indicated Faults
January 2021	PD	S	S	Indicated Partial Discharge and Stray Gassing

The results of the identification of Duval Triangle 1 show an indication of partial discharge (PD) in each test sample which has the formation of hydrocarbon gas, while the identification of Duval Triangles 4 and 5 shows an indication of stray gassing (S).

D. Application of Duval Pentagon

The DGA test results of the GT 3.1 transformer will be analyzed using the Duval Pentagon 1 method, with the input parameters of the five hydrocarbon gases (H2, CH4, C2H2, C2H4, and C2H6), if there is no concentration of hydrocarbon gas then the Duval Pentagon cannot be used. Whereas the use of Duval Pentagon 2 based on the interpretation of CO and CO2 gases is only used in the test sample on January 12, 2021.

TABLE XI
RESULT OF DUVAL PENTAGON IDENTIFICATION

Date	DPM1	DPM2	Conclusion
July 2019	PD	Not used	Indicated Partial Discharge
September 2019	PD	Not used	Indicated Partial Discharge
November 2019	Not used	Not used	No Indicated Faults
January 2020	PD	Not used	Indicated Partial Discharge
March 2020	Not used	Not used	No Indicated Faults
May 2020	Not used	Not used	No Indicated Faults
January 2021	S	S	Indicated Stray Gassing

The results of identification with Duval Pentagon 1 show partial discharge (PD) except for the January 2021 test sample showing stray gassing (S) results. The results of Duval Pentagon 2 also show stray gassing (S) in the same test sample.

In indicating the possibility of disturbances occurring, Duval Triangle 1 and Duval Pentagon 1 are used as the main benchmark because they show the results of basic faults, while Duval Triangles 4, 5, and Pentagon 2 are used whether there are sub-type faults although they can be shows basic faults as well. In the January 2021 test sample, there is an indication of a combined partial discharge (PD) with stray gassing (S). In [18] shows that the transformer can still operate normally with stray gassing (S) conditions, and historically the GT 3.1 transformer tends to be in a partial discharge (PD) condition so the recommended treatment is to perform a partial discharge (PD) check on the transformer. However, stray gassing (S) conditions still need to be monitored for insulating oil conditions, to ensure the correctness of stray gassing (S) indications and their effect on paper and oil insulation conditions [19].

IV. CONCLUSION

Identification of the condition of the transformer using the Random Forest-based Duval methods has been carried out using the DGA test sample from the insulating oil of the GT 3.1 PLTGU Grati transformer. From the test sample data, it was found that transformers tend to be in PD (Partial Discharge) conditions, but in samples that have "ALERT" status in the IEC 60599 standard identified using a Duval Triangle indicating PD (Partial Discharge) and S (Stay Gassing) conditions, while using a Duval Pentagon only shows the S (Stray Gassing) condition. The results of identification using the Duval Triangle and Pentagon it does not always show the same results on the same test sample, so it is necessary to identify the history of DGA testing to get accurate results. It could be interesting to consider the DGA interpretation method with different use, depending on their meaning to the fault identification. This mechanism would aid to understand the same problems where the results are different between two or more methods.

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