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Duval Triangle-Based Dissolved Gas Analysis using GNU Octave for Transformer Fault Detection

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ABSTRACT

Transformers are vital components in electrical power systems. However, they are also susceptible to various types of failures, including thermal and electrical faults caused by the formation of electromotive force, which, if left unaddressed, may result in degradation of the oil insulation. One effective approach to mitigate such issues is to conduct feasibility testing and oil analysis, commonly known as Dissolved Gas Analysis (DGA), which examines the condition of the insulating fluid within the transformer. In this study, gas concentration levels were identified as follows: C_2H_4 = 9 ppm, CH_4 = 4 ppm, and C_2H_2 = 11 ppm. These values were visualized using the Duval Triangle Method, an established technique for analyzing gas content by measuring the concentration of three primary gases: Methane (CH_4), Ethylene (C_2H_4), and Acetylene (C_2H_2), all of which dissolve in the transformer oil. The advantage of this method lies in its ability to serve as an early fault detection tool for transformer oil. The analysis results indicated an electrical fault categorized as a High Energy Discharge in zone D2, identified by a single plotted point where the three gas lines intersect on the triangle diagram. This type of discharge is predominantly associated with Acetylene gas (C_2H_2) and is typically triggered by intense internal arcing within the transformer. The interpretation was further implemented using an automated data plotting system in GNU Octave, serving as a Transformer Fault Detection tool and computational software that utilizes the C++ programming language for data processing and visualization.

Keywords:
Dissolved gas analysis;
Duval Triangle Method;
transformer oil;
high energy discharge;
GNU Octave;
transformer fault detection.

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1. INTRODUCTION

Transformers play a critical role in ensuring the reliable stepping up and stepping down of electrical voltage, two fundamental processes necessary for transmitting electrical power from generation stations to end users. Therefore, maintaining the continuous and dependable operation of these devices around the clock, throughout the entire year, is of paramount importance [1]. Oil-immersed power transformers represent some of the most critical assets within the electrical power grid. They serve essential functions across electricity generation, transmission, and distribution, forming the backbone of the entire power infrastructure [2][3]. Condition monitoring and asset management in transformers are critical priorities for all electric utility providers. Given that a typical power grid may operate thousands of transformers, monitoring their condition can quickly become a resource-intensive and time-consuming task [4]. Due to their importance, regular maintenance is vital to sustain their performance as transformers are susceptible to various types of failures: thermal, electrical, and mechanical, that can lead to serious damage if not promptly detected and mitigated. Continuous online monitoring and assessment of transformer performance are vital to maintaining system reliability.

The operational health of a power transformer largely relies on the condition of its insulating oil during normal operation. Thorough monitoring and analysis of the insulation system are crucial to maintaining consistent performance. Early detection of transformer faults is therefore vital to ensure the reliable operation of the electrical power system. Within the transformer, the oil functions both as a cooling agent and as a dielectric medium [5]. In 2019, IEEE introduced an international standard for Dissolved Gas Analysis (DGA) to enhance diagnostic accuracy for transformers using mineral oil, although it presents limitations when applied to renewable energy transformers. In 2022, further developments were made in interpreting DGA fault severity by incorporating screening test statistics and optimization curves based on transformer failure data [6].

Among various techniques, Dissolved Gas Analysis (DGA) has proven to be an effective approach for real-time evaluation of transformer operational conditions [7][8] and one of the most commonly adopted diagnostic methods for power transformers currently used by electric utilities around the world [9]. Identifying potential internal faults within power transformers is essential for safeguarding the stability and reliability of the power system. Dissolved Gas Analysis (DGA) is widely acknowledged as an effective diagnostic method for detecting faults in power transformers [10][11]. Serves as a valuable diagnostic tool for anticipating potential faults before they occur. However, DGA-based incipient fault detection has not always produced consistently reliable results across all conditions [12][13]. Various techniques are available for fault identification using DGA, including the Duval Triangle, Duval Pentagon, Doernenburg Ratios, Rogers Ratios, IEC Ratios, and the Key Gas method [13].

To avoid additional damage, as mentioned by [14]. The Duval Triangle diagnostic method, developed by Michel Duval in 1974, is designed for oil-insulated high-voltage equipment, particularly transformers. It relies on the analysis of three Hydrocarbon gases: Methane (CH_4), Ethylene (C_2H_4), and Acetylene (C_2H_2), which represent increasing energy levels associated with gas generation in transformers under operation. In this method, fault diagnosis is conducted by visualizing the relative concentrations of these dissolved gases on a triangular diagram. The Duval Triangle method is a widely accepted approach for diagnosing incipient faults in transformers, valued for its simplicity, ease of interpretation, and diagnostic effectiveness. It is a graphical technique in which the triangular area is divided into seven distinct zones, each corresponding to a specific fault type. This method relies on the relative concentrations of three key fault gases: Methane (CH_4), Ethylene (C_2H_4), and Acetylene (C_2H_2), to identify seven possible fault conditions [12].

In the current digital era, it has become increasingly uncommon to encounter applications that are universally accessible to all users. The demand for numerical software that is both computationally efficient and user-friendly is widely acknowledged and generally undisputed. However, several fundamental questions in this area remain unresolved. Concerning to user-friendliness, no single programming paradigm has yet established itself as the dominant standard. More importantly, it remains uncertain whether a universal, one-size-fits-all solution will ever be achievable, given the significantly diverse needs and expectations of different user groups regarding numerical computing tools. On one hand, a large portion of application developers and end users prioritize ease of use and prefer streamlined development workflows, often favoring intuitive, point-and-click interfaces [15]. Accordingly, this study employs GNU Octave to streamline the process and enhance time efficiency, especially in situations where manual interpretation is not feasible due to time constraints. This is consistent with the findings of [17], which likewise utilized GNU Octave.

Unlike prior research, the present study focuses on the application of open-access software to determine the type of electrical fault in transformer insulating oil based on the Duval Triangle method. While several prior studies have successfully applied the Duval Triangle either manually or using commercial software, this study has explored its integration into open-source platforms such as GNU Octave. This represents a significant opportunity to provide diagnostic tools that are accessible, cost-effective, and user-friendly for both industries and academia. This research aimed to assess the condition of transformer oil using the Duval Triangle Method and a GNU Octave-assisted program, enabling early maintenance decisions and preventing severe equipment failures. The main contribution of this work lies in demonstrating a low-cost, accessible, and automated diagnostic approach using GNU Octave as an alternative to commercial applications, thereby supporting wider adoption of condition-based monitoring practices in the electrical power industry.

Octave has a syntax that is compatible with MATLAB, making it a popular free alternative for users who wish to perform mathematical modeling, data analysis, and simulations without relying on MATLAB [15]. Data processing in this research, using the Duval Triangle Method, was carried out manually, both in plotting and in calculations. To simplify the analysis process in identifying the cause [13] of electrical faults in transformer oil, the online software Octave was utilized. This software enables online detection of fault causes simply by inputting the ppm values of the three gases. The Octave software contains program codes to execute user-defined commands. Therefore, Octave is built using the C++ programming language. Octave is a free, GNU-based software designed for numerical analysis and offers functionality comparable to MATLAB. It was developed by John E. Watton and was first released in 1988. The online version of Octave is preferred to allow students or users flexible access anytime and anywhere [16]. It is an open-source software based on a high-level programming language used for numerical computation. Octave features syntax compatible with MATLAB, making it a popular free alternative for users seeking to perform mathematical modeling, data analysis, and simulations without the need to use MATLAB.

2. RESEARCH METHODS

2.1 Data Collection

This research was conducted through a quantitative diagnostic approach using the Dissolved Gas Analysis (DGA) method to evaluate the condition of transformer oil at PT. PLN Indonesia Power, especially on Station Service Transformer (SST). The objective was to determine the type and severity of internal faults by analyzing the concentration of dissolved gases in the transformer oil and mapping the results using Duval Triangle manually first before the automatic program is used.

The data consisted of gas concentrations in ppm of key indicator gases, including Methane (CH_4), Acetylene (C_2H_2), and Ethylene (C_2H_4), collected from November 2024 and April 2025. The DGA begins with the collection of an oil sample from the transformer. The sample then undergoes testing and procedures to identify and determine the quantity of dissolved gases. The gases commonly detected during DGA include Ethane (C_2H_6), Ethylene (C_2H_4), Oxygen (O_2), Methane (CH_4), Acetylene (C_2H_2), Nitrogen (N_2), and Hydrogen (H_2), which are typically found dissolved in the transformer [4]. The sample was collected from Figure 1, Transformer SST 1.2 on Gas Turbine 2, Combined Cycle Plant, block 1. The Transformer unit is a three-phase and two-winding transformer, constructed in 1993 based on the IEC 76 standard. This transformer operates with two types of cooling systems, applied according to the required power load (MW), which is ONAN (Oil Natural Air Natural) and ONAF (Oil Natural Air Forced). Using Shell Diala S4 ZX-I as the insulation oil. It is designed to operate at a frequency of 50 Hz.

Figure 1. Unit Station Service Transformer

The process begins by preparing the necessary equipment, such as a bottle, a small jerry can, combination pliers, needle-nose pliers, tubing, and a syringe. Next, the four bolts on the valve are carefully loosened while ensuring the valve remains in the closed position to prevent leakage. The tubing is then securely attached to both the syringe and the valve to avoid air ingress during sampling. The valve is gradually opened to allow transformer oil to flow; the initial oil flow is discharged to stabilize the flow rate. The oil is then drawn carefully into the syringe until it is full, and the syringe valve is closed. Any air bubbles present in the syringe are removed by slowly discharging a small amount of oil to release the trapped air. The syringe is then refilled until the volume exceeds 50 ml, ensuring no air remains inside. If the volume does not meet the minimum requirement, additional oil must be collected. Once the oil sample meets the volume and air-free criteria, it is ready for testing using the Dissolved Gas Analysis (DGA) method to evaluate the condition of the transformer oil.

2.2 Dissolved Gas Analysis

Dissolved Gas Analysis (DGA) is a method used to analyze the dissolved gases present in transformer oil. This technique is essential for diagnosing the condition and health of a transformer, as the presence and composition of dissolved gases can provide early indications of potential faults or deterioration within the insulation system. Gas measurement involves the use of analytical instruments designed to separate, identify, and quantify components within a gas mixture or volatile compounds. These instruments play a critical role across various fields, including scientific research, quality control, and industrial diagnostics. In the application of Dissolved Gas Analysis (DGA) for transformer oil, DGA instruments are used to detect various types of gases generated as a result of oil or insulation degradation, which typically occurs due to internal faults within the transformer.

In this study, the DGA analysis was conducted using the Kelman Transport X^2, which is a portable on-site DGA device, which is capable of performing onboard diagnostics for Duval's Triangle, Roger's Ratio, Key Gas, and the Japanese ETRA method. Kelman Transport X^2 is a portable device resembling a "lab in a box," capable of delivering comprehensive analysis with significantly shortened processing times. In critical conditions, its ability to perform dissolved gas analysis (DGA) on-site in under 30 minutes enables asset owners to assess the condition of a transformer directly, allowing operational decisions to be made as early as possible. The output from this device is provided in CSV file format and displayed on screen, with a hardcopy generated via a 2-inch thermal printer.

Figure 2. The DGA analysis instrument

The procedure begins by switching on the DGA device and allowing a 30-minute warm-up period as illustrated in Figure 2. Once ready, initiate the process by selecting “Start New Measurement.” Then, configure the system by selecting the appropriate equipment type “Transformer”, equipment location (the specific unit to be tested), and sampling point “Bottom” as the sample is taken from the lower part of the transformer. Choose “Oil Sample” as the source type, and confirm all settings before proceeding. Next, ensure all necessary tools, such as the sampling bottle, magnet, and syringe, are clean and dry. Install the bottle with its probe and insert the magnet inside. Continue with the purging process for five minutes to eliminate air or contaminants. Attach the syringe connector carefully, then insert the syringe into the sampling bottle promptly once instructed, being mindful of the time constraint. Hold the connector securely to prevent syringe head damage while injecting the oil sample quickly and precisely. Once the sample is collected, the DGA measurement will begin automatically. Upon completion, gas concentration parameters will appear on the display.

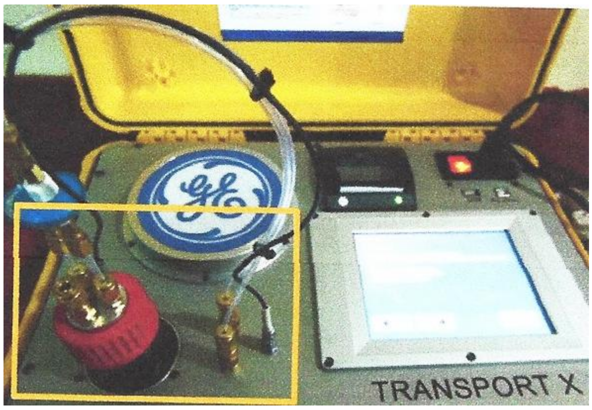

Figure 3. Dissolved Gas Analysis (DGA) measuring instrument

During operation, transformer oil may degrade and produce dissolved gases. Several key gases generated and analyzed in DGA (Dissolved Gas Analysis) testing include:

1. Hydrogen (H_2): Formed as a result of energy disturbances such as overheating, and often serves as an indicator of insulation failure.
2. Methane (CH_4): Generated at low temperatures and may indicate early-stage issues such as mild overheating.
3. Ethylene (C_2H_4): Produced from more intense heating and can signal thermal faults.
4. Acetylene (C_2H_2): This gas typically indicates more severe failures, such as electrical arcing, and can be generated at temperatures exceeding 700°C.
5. Carbon Monoxide (CO) and Carbon Dioxide (CO_2): These gases indicate combustion or decomposition of insulating materials, such as oil or cellulose.

2.3 Duval Triangle Method

The Duval Triangle Method illustrates the relationship between the concentrations of three gases in the form of a triangular diagram, where each corner of the triangle represents one specific gas. The position of the point representing the gas ratio can indicate the type of fault that may be occurring, such as overheating, arcing, or insulation failure. Figure 4 illustrates the Duval Triangle diagram.

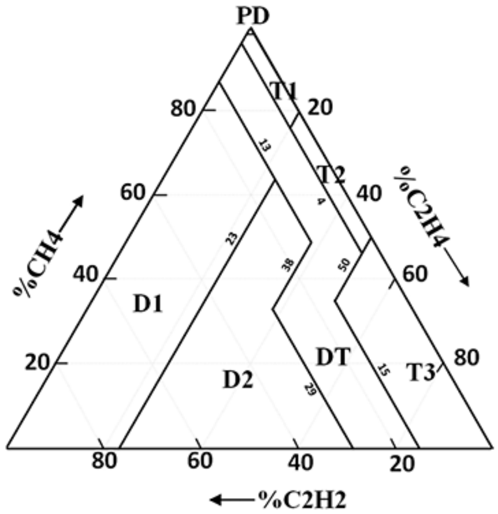

Figure 4. The duval Triangle diagram

Each corner of the triangle represents 100% of one of the gases: CH_4 at the left corner, C_2H_4 at the right corner, and C_2H_2 at the bottom corner. Draw lines from each axis toward the point where the three gas values intersect, indicating the location of the point within the triangle. This diagram is also divided into several zones, such as D1, D2, and T1 through T3, each representing a specific level of degradation or risk of damage to the transformer oil. By analyzing the position of the point resulting from the combination of gas percentage values, the condition of the oil can be evaluated. The Duval Triangle Method has been established as an international standard under IEEE C57.104 and IEC 60599.

The fundamental principle of the Duval Triangle method relies on the concentrations of three key gases produced from the decomposition of insulating oil to determine the type of fault occurring in a transformer. These three gases are:

1. Methane (CH_4) – An early indicator of faults caused by partial discharges or electrical discharges.
2. Ethylene (C_2H_4) – Associated with medium to high-level thermal faults.
3. Acetylene (C_2H_2) – Indicates the presence of electrical arcing or high-energy discharge faults.

The concentrations of these gases are normalized into total percentages (%) and then mapped onto the triangle to identify the fault category. The gas concentrations initially detected in parts per million (ppm) from DGA results must be converted into percentages using this formula (Equation 1):

$$\text{Percentage } (\%) = \frac{Each\ Gas\ (ppm)}{Methane + Acetylene + Ethylene} \times 100\% \quad (1)$$

This calculation produces a point location within the triangle based on the relative proportions of Ethylene and Acetylene, which define the direction and position of the gas mixture. The resulting values (percentage of three gases) were then plotted onto the triangle to determine the fault zone according to classification standards from IEEE C57.104. After the gas concentration data is converted into relative percentages of three key gases, the next step is to map these values onto the Duval Triangle diagram. This triangle is a graphical diagnostic tool used to identify the type of internal faults in transformers, such as partial discharges, low or high energy arcing, and thermal faults.

Table 1 presents the characteristics of transformer faults that occur when the gas levels within the transformer have reached a deteriorated condition.

Table 1. Fault classification of duval triangle diagram

No.	Zone	Fault
1	PD	Partial Discharge
2	D1	Low energy discharge
3	D2	High energy discharge
4	T1	Thermal faults under 300° C
5	T2	Thermal faults between 300° C and 700° C
6	T3	Thermal faults above 700° C
7	DT	A combination of thermal and electrical faults

1. PD (Partial Discharge): Dominated by CH_4, indicating partial electrical discharge.
2. D1 (Discharge of Low Energy): Low-energy electrical discharge, with a moderate presence of C_2H_2.
3. D2 (Discharge of High Energy): High-energy electrical discharge, characterized by a high concentration of C_2H_2.

4. T1 (Thermal < 300°C): Low-temperature thermal fault, typically dominated by CH_4.
5. T2 (Thermal 300°C – 700°C): Medium-temperature thermal fault, dominated by C_2H_4.
6. T3 (Thermal > 700°C): High-temperature thermal fault, usually indicating severe degradation of transformer oil.
7. DT (Mix of Thermal and Electrical): A combination of thermal degradation and high-energy electrical discharge.

These are the steps for plotting the Duval Triangle Diagram

1. Collecting DGA Test Result: obtain the concentration values (in ppm) of three key gases from Dissolved Gas Analysis: Methane (CH_4), Ethylene (C_2H_4), and Acetylene (C_2H_2).
2. Convert ppm to percentages and calculate as the formula (1).
3. Plotting on the Duval Triangle: Plotting begins by marking the percentage of each gas on the Duval Triangle diagram, then drawing straight lines from each marked point until they intersect at a single point. Each corner represents 100% of one gas. When the straight lines representing the three gas percentages meet, the point of intersection indicates the diagnostic result of the transformer oil condition.

2.4 Program Implementation

In this study, the mapping process was enhanced and automated using GNU Octave, an open-source numerical computing software. The program allows users to input gas concentration values (ppm) and convert them to display the fault point directly on the Duval Triangle. This method enables faster and more accurate identification without the need for manual plotting.

Figure 5. The GNU Octave software

In the context of this research, the version of the software used in this study is GNU Octave 10.1.0 (64-bit), although a newer version, 10.2.0, is currently available. Figure 5 shows the icon of the GNU Octave software, and Figure 6 shows the main interface of the Octave software. With the aid of Octave, users only need to input the concentration values of specific gases such as methane, ethylene, and acetylene (in ppm), and the software will automatically visualize the diagnostic point on the Duval diagram to identify potential internal faults, such as overheating, partial discharge, or arcing. Therefore, Octave serves as an efficient tool that supports rapid, data-driven analysis of transformer conditions. Here the steps to create the program in GNU Octave.

1. Open the GNU Octave Software: Launch the Octave desktop interface as Figure 6.

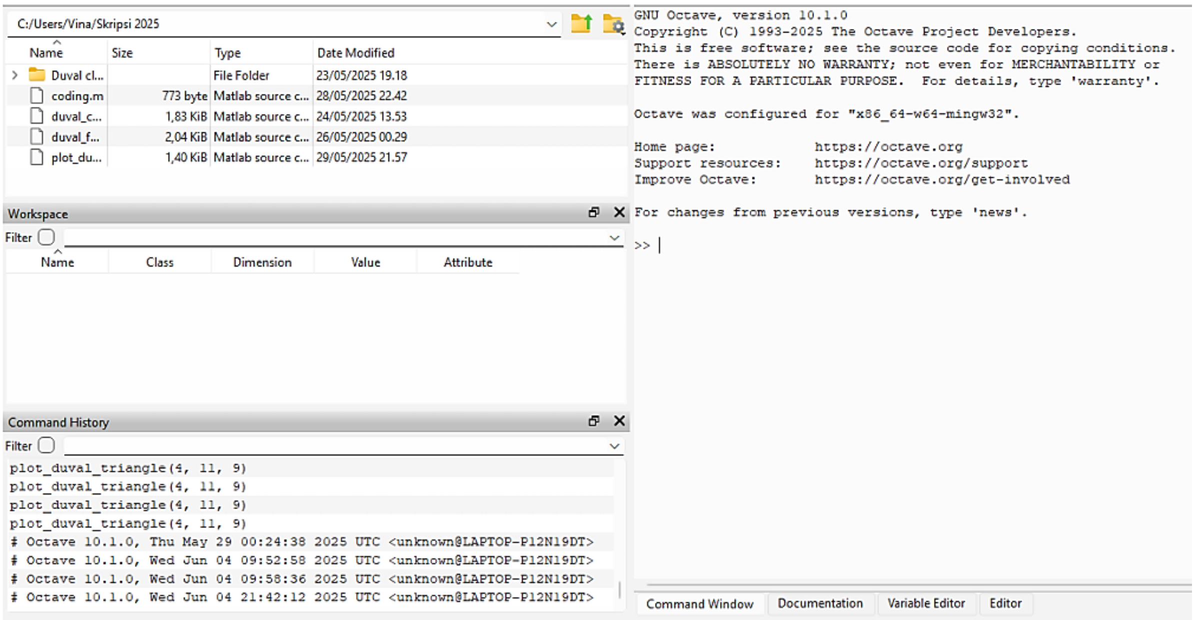

Figure 6. The main interface of the Octave software

2. Create a new script. Go to the “Edit” tab and click New Script to create a (.m) file where the function or program will be written. To start the analysis, enter the program code into the Editor menu.

3. Save the script using the same name as the file (.m) extension, as the program will not run properly if the file name is different.
4. Run the script by defining or entering the function with values in the Command Window.
   function: duval_fault_classification (CH4, C2H2, C2H4)
5. After pressing Enter to run the function, the analysis result indicating the fault type zone will be displayed automatically.

2.5 Standardization

In this study, the DGA method is interpreted using the Duval Triangle; therefore, this research adopts relevant international standards to align with the current methodology. This ensures a clear understanding of the safe and unsafe threshold limits for the ppm value variables.

The IEEE C57.104 Standard (IEEE Guide for the Interpretation of Gases in Oil-Immersed Transformers) as shown in Table 2, is a standard published by the Institute of Electrical and Electronics Engineers (IEEE) that provides guidelines for the analysis and interpretation of Dissolved Gas Analysis (DGA) in transformer insulating oil. This standard is designed to assist operators in detecting, identifying, and evaluating potential faults in power transformers and other electrical equipment that use oil as an insulating medium.

Table 2. Gas content standard according to IEEE C57.104

Gas Content	Maximum Limit
Hydrogen (H_2)	100 ppm
Methane (CH_4)	120 ppm
Acetylene (C_2H_2)	1 ppm
Ethylene (C_2H_4)	50 ppm
Ethane (C_2H_6)	65 ppm
Carbon Monoxide (CO)	350 ppm
Carbon Dioxide (CO_2)	2500 ppm

IEC 60599 as shown in Table 3, is an international standard issued by the International Electrotechnical Commission (IEC). It provides guidance for diagnosing the condition of transformers and other oil-filled electrical equipment using dissolved gas analysis (DGA). The standard outlines methods for detecting and interpreting gases produced from the degradation of insulating oil or solid insulating materials due to electrical or thermal stresses.

Table 3. Standard according to IEC 60599

Case	Characteristic fault	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
PD	Partial discharge	NS	< 0,1	< 0,2
D1	Discharges of low energy	> 1	0,1 – 0,5	> 1
D2	Discharges of high energy	0,6 – 2,5	0,1 – 1	> 2
T1	Thermal fault T < 300°C	NS	> 1 but not NS	> 1
T2	Thermal fault 300°C < T < 700°C	< 0,1	> 1	1 – 4
T3	Thermal fault > 700°C	< 0,2	> 1	> 4
NS = Non-significant, regardless of the value				

3. RESULTS AND DISCUSSION

3.1 Dissolved Gas Analysis (DGA) Test Results

Figure 7 shows the results of dissolved gas analysis over the last eight years, but this study will only use the latest DGA data on April 11, 2025, as written in Table 4. The initial increase occurred on November 15, 2024 during routine measurements one month after purification on October 15 and 17, 2024; therefore, the high C2H2 value is only a sampling test value in the conservator, not to be used as a comparative value for analysis.

Table 4. PPM results from the last one-year period

Date	Hydrogen (H2)	Water (H2O	Carbon Dioxide (CO2)	Carbon Monoxide (CO)	Ethylene (C2H4)	Ethane (C2H6)	Methane (CH4)	Acetylene (C2H2)	IEEE Std.
10/15/24	5	21	40	11	3	4	2	1,5	Con. 1
10/15/24	5	27	388	35	78	8	30	264,2	Con. 4
10/15/24	5	29	375	38	80	10	30	270,4	Con. 4
10/16/24	5	34	270	19	17	3	7	60,9	Con. 4
04/11/25	26	30	1171	89	9	7	4	11	Con. 3

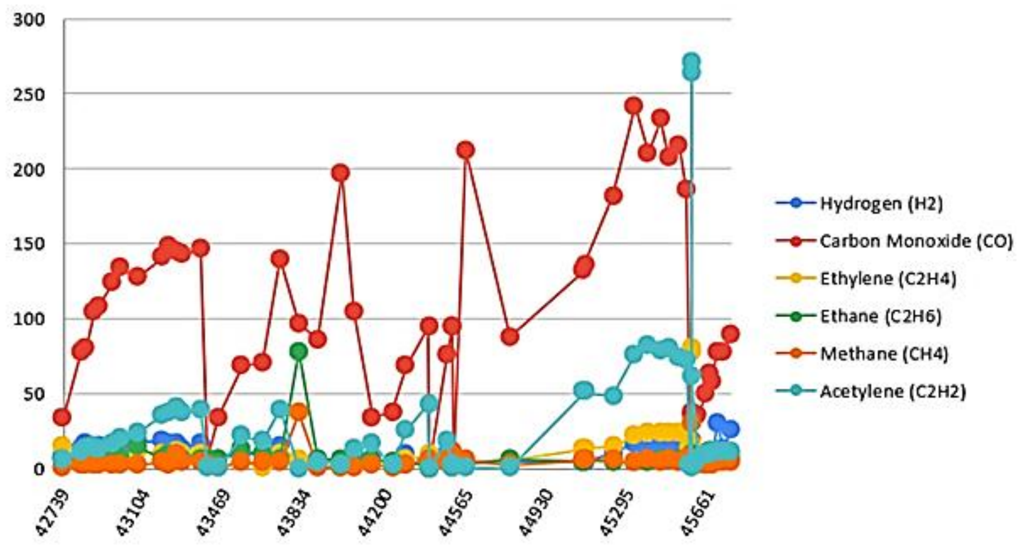

Figure 7. PPM value diagram from recent years

The Ethylene (C_2H_4) gas, represented in yellow on the graph, shows a relatively stable concentration pattern throughout the observation period, with values ranging between approximately 10 and 15 ppm. No significant spikes were observed for this gas, indicating that C_2H_4 was not the dominant gas concerning to severe thermal faults in the transformer during that time. In DGA analysis, ethylene typically appears in large quantities when significant heating of transformer oil occurs, especially at high temperatures (above 500°C). Since the levels remained low, there is no strong indication of severe thermal degradation. Nevertheless, the presence of ethylene remains important, particularly when analyzed in conjunction with other hydrocarbon gases such as Ethane (C_2H_6) and Methane (CH_4). The combination of these gases can provide a more comprehensive overview of potential mild to moderate overheating within the system, making ethylene a relevant indicator in evaluating the condition of the transformer.

Methane (CH_4) gas, represented in orange on the graph, showed a slight increase beginning in mid-2023, with concentrations reaching approximately 12 ppm. Although the value is still considered low, the upward trend aligns with patterns typically associated with low energy discharges, electrical energy releases at low levels that do not yet cause significant damage but indicate abnormal electrical activity within the transformer. Methane is often produced under conditions such as corona or partial discharge. While these are not as critical as arcing or severe overheating, the increase should still be noted as an early warning sign of potential disturbance. If this trend continues or rises alongside other gases such as hydrogen (H_2) or Acetylene (C_2H_2), it could signal a more serious fault developing and warrant further investigation or action.

Acetylene (C_2H_2) gas, represented in light blue on the graph, showed a sharp spike from mid-2024 through the end of the year. One of the highest recorded concentrations occurred on October 15, 2024, reaching 264.2 ppm. This is an extremely high value and serves as a strong indicator of high-energy discharge, specifically electrical arcing caused by severe internal faults within the transformer. According to the Duval Triangle interpretation method, such a dominant concentration of C_2H_2 would place the diagnostic point in Zone D2, which technically indicates a fault due to arcing in internal components such as the tap changer, terminals, or solid insulation. However, following this spike, there was a significant decline in C_2H_2 concentration, suggesting that corrective actions may have been taken—such as component replacement, arc cleaning, or OLTC servicing—effectively eliminating or reducing the source of the electrical fault. The significant increase in C_2H_2 (exceeding 4 ppm) near the end of the monitoring period, particularly on October 15 and 16, 2024, aligns with early indications of arcing activity. Concluded from Table 4, the results of oil ppm used in the Duval Triangle Method can be grouped in the following table.

Table 5. The ppm values applied

Content Analysis April 11, 2025		
Gas Type	**PPM**	**IEEE Normal Limits**
Ethylene (C2H4)	9	50/100/200
Methane (CH4)	4	120/400/1000
Acetylene (C2H2)	11	2/9/35

Although the levels of Ethylene and Methane remain within safe limits, the Acetylene concentration reaching 11 ppm indicates a potential occurrence of arcing within the transformer. This suggests an abnormal condition which, although not yet critical, is sufficient to classify the transformer under Condition 3 according to the IEEE C57.104 standard.

1. Ethylene (C_2H_4) = 9 ppm
   Ethylene gas appears as an indication of overheating in the transformer's insulating oil. A value of 9 ppm is still below the first threshold (50 ppm), indicating a normal condition with no signs of severe overheating.
2. Methane (CH_4) = 4 ppm
   Methane is a gas typically formed due to low-energy discharges or mild heating. A concentration of 4 ppm is very low and does not indicate any major issues.
3. Acetylene (C_2H_2) = 11 ppm
   Acetylene is the most critical gas, as it is only produced in the presence of high-energy arcing or internal electrical discharges. Acetylene (C_2H_2) serves as a direct indicator of internal electrical arcing within the transformer.

The statement that an acetylene (C_2H_2) level of 11 ppm has exceeded the threshold and falls under Condition 3 is based on the international standard IEEE C57.104, which serves as a primary reference in the interpretation of Dissolved Gas Analysis (DGA). It is important to note that in this study, the IEEE C57.104 standard classifies gas conditions based on concentration levels, but it does not directly specify the type of fault (such as arcing) based solely on a single gas value.

3.2 Calculation of Dissolved Gas Analysis Data

Based on the data obtained from the research site at PT. PLN Indonesia Power, the values were calculated using the Duval Triangle Method in accordance with the established formula. Given:
Ppm Methane (CH_4) = 4
Ppm Ethylene (C_2H_4) = 9
Ppm Acetylene (C_2H_2) = 11

Calculate the percentage of each gas according to Equation (1),

$$\text{Percentage } (\%) = \frac{Each\ Gas\ (ppm)}{Methane + Acetylene + Ethylene} \times 100\%$$

Therefore, the resulting percentage values is $\%CH_4$ = 16%, $\%C_2H_4$ = 37,5 %, dan $\%C_2H_2$ = 45%. The percentages represent the internal fault in the transformer and serve as the basis for mapping into the fault zones.

3.3 Plotting data onto the Duval Triangle diagram

The Duval Triangle Method is not designed to determine whether gas levels are high or low, but rather to analyze the relative composition and the underlying cause of failure based on the three key gases. If Acetylene (C_2H_2) is the dominant component among the total of the three gases, the plotted point will fall within the D2 zone, indicating the presence of arcing (electrical discharge). Not all transformer faults can be identified or plotted using the Duval Triangle Method. This method is only applicable when an electrical fault occurs. Once the percentage values of each gas concentration (in ppm) have been determined, the data can then be plotted onto the Duval Triangle diagram as shown in Figure 8.

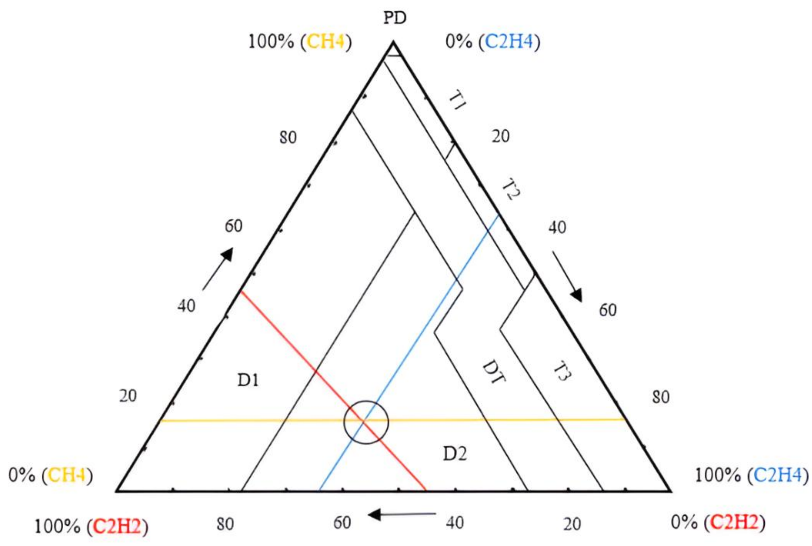

Figure 8. The result of percentage point mapping

A single intersection point was identified among the three gas lines, located in Zone D2, which indicates a High Energy Discharge. This type of discharge is dominated by Acetylene (C_2H_2) gas and is typically caused by intense electrical arcing within the transformer. A D2-type fault involving high-energy discharge poses a serious risk to windings, solid or liquid insulation, and may lead to inter-phase short circuits if left unaddressed over time.

Fault analysis on the transformer was conducted using the Duval Triangle Method, aimed at identifying types of internal faults based on the concentration of dissolved gases, particularly CH_4, C_2H_2, and C_2H_4. The results from percentage calculations and point mapping on the triangle revealed that several samples fall within the D2 zone, indicating the presence of high-energy discharge. These findings are consistent with the statement in IEEE C57.104, which notes that a dominance of Acetylene (C_2H_2) in the dissolved gas composition generally signifies arcing or high-energy discharges that may damage the solid or liquid insulation in the transformer. Based on the C_2H_2 level exceeding 2 ppm, the high-energy discharge fault is categorized as severe. According to IEEE C57.104, this concentration falls under Condition 3, indicating urgent maintenance is required. If the arcing fault indicated by Zone D2 persists without corrective action, the continued thermal and electrical stress may degrade the winding insulation, leading to phase-to-phase short circuits. A fault score of 3 out of 4 is assigned based on gas intensity and type, placing the condition in the 'Moderate Risk' category requiring planned maintenance within 1–2 weeks.

Following the fault prediction, it is recommended to immediately conduct an inspection of the Transformer Unit SST 1.2 to confirm the suspected high-energy discharge fault and proceed with the following actions:

1. Verify and retest the DGA to ensure the accuracy of the gas analysis data.
2. Evaluate the transformer's operating condition, including checking operating parameters (load, temperature, voltage) to detect any overloading or thermal and electrical stress, and reviewing the disturbance or flashover history that may have triggered the high-energy discharge.
3. Conduct visual inspection and additional testing, including internal inspection for signs of carbonization, melted metal, or arcing, as well as performing supplementary tests such as:
   a. Insulation resistance measurement
   b. Tan Delta test (power factor test)
   c. Partial Discharge (PD) testing
   d. Thermal imagining to detect potential hot spots

3.4 Data Processing Using GNU Octave Software

The provided script, named duval_fault_classification.m, is an Octave-based diagnostic program designed to analyze dissolved gas concentrations in transformer oil using the Duval Triangle method. This program is developed to assist in identifying potential transformer faults such as thermal overheating or arcing based on the concentration ratios of Methane (CH_4), Acetylene (C_2H_2), and Ethylene (C_2H_4). These gases are commonly produced due to electrical or thermal stresses in transformer insulation systems.

The program workflow can be summarized as follows:

1. User Input Collection
   The program prompts the user to enter gas concentration values (in ppm) for CH_4, C_2H_2, and C_2H_4. It then performs validation to ensure non-negative and non-empty values.
2. Gas Ratio Calculation
   The total concentration is computed, followed by the normalization of each gas into percentage form. These percentages serve as the basis for classification within the Duval Triangle.
3. Fault Classification Using Duval Rules
   The program uses predefined conditional logic based on IEEE/IEC Duval Triangle standards to determine which zone the input falls into, such as:
   a. PD (Partial Discharge)
   b. D1 (Low Energy Arcing)
   c. D2 (High Energy Arcing)
   d. T1, T2, T3 (Thermal faults by severity of temperature)
   Additionally, the program accounts for transition zones and uncertain conditions by interpreting dominant gas concentrations.
4. Result Output and Interpretation
   The diagnosis results, including zone code, fault type, severity level, and recommended action, are displayed in tabular format. Reference information about each zone is also provided for clarity.

The program execution is performed by pressing the "Run" button, represented by a triangle icon located at the top of the editor window. Once the button is activated, the user returns to the Command Window tab, where the program will prompt for manual input of dissolved gas concentration values (in ppm). The user must enter these values in the specified order and press Ente*r* after each entry. This process is repeated for each required gas: CH_4, C_2H_2, and C_2H_4. After all gas values have been inputted, the user presses Enter once more to execute the analysis process. The fault classification results, based on the Duval Triangle method, will then be displayed in table format within the Command Window. This output includes the percentage of each gas and the type of fault that has been identified.

3.5 Discussion

The diagnostic results of this study regarding high-energy discharges located in the D2 zone are consistent with the findings of [10] and [15], in which C_2H_2 levels exceeding 10 ppm indicate an increase beyond the safe limit for conditions 1–2. However, the automated approach applied in this study can reduce the processing time [17]. While recent studies have significantly advanced transformer fault diagnosis through machine learning, predictive modeling, and hybrid AI approaches, limited attention has been given to developing accessible, open-source tools for direct Duval Triangle analysis. This study addresses that gap by proposing a practical and low-cost approach using GNU Octave to visualize and classify transformer faults based on dissolved gas concentration—bridging the disconnect between high-level algorithmic methods and user-friendly field applications. In contrast, references such as [13] generally focus on improving classification accuracy through artificial intelligence methods such as Support Vector Machines (SVM), Decision Trees, or Bayesian Networks. These studies place greater emphasis on the development of predictive models, rather than direct visualization and automation based on field data. In terms of diagnostic methodology, this study employs a visual approach using the Duval Triangle to identify fault zones (T1–T3, D1–D2, PD, DT). The gas concentration percentages are calculated explicitly and plotted within an Octave-based system. In contrast, references such as [13] prioritize model optimization techniques, such as Teaching-Learning-Based Optimization or AI-based feature fusion, rather than direct visual interpretation using the Duval Triangle.

This study addresses the gap in the lack of local research utilizing GNU Octave for the automated interpretation of transformer fault zones. It also responds to the limited use of real-world DGA input visualization directly mapped into the Duval Triangle for diagnostic purposes based on the IEEE C57.104 standard. Previous studies have yet to integrate a simple function-based automation system that can assist technicians or students in interpreting diagnostic results more efficiently.

4. CONCLUSION

This research has met its primary objective of identifying transformer faults based on the Duval Triangle method using automated computation in GNU Octave. The analysis revealed that the gas concentration pattern, particularly the high proportion of acetylene, indicates a high-energy discharge fault, classified in zone D2. These results are consistent with established diagnostic standards (IEEE C57.104) and reinforce findings from prior literature. Unlike previous studies relying on advanced algorithms, this study demonstrates that a straightforward, open-access computational tool can effectively support early-stage fault interpretation. These outcomes validate the hypothesis and open new directions for research involving real-time diagnostic applications or integration with AI-based predictive systems. However, this study has a limitation in terms of the visualization of the Duval Triangle within the Octave program. The visualization remains descriptive and is not yet interactive or fully integrated as an automated triangular diagram. As a result, the visual interpretation of the classified fault zone still requires manual steps or external assistance.

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