Dissolved Gases Analysis Comparison of Electrical Faults Between Rice Bran Oil and Mineral Oil Insulation Systems

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***Abstract*— Dissolved gas analysis (DGA) of transformers can reveal electrical stresses encountered by oil-immersed power transformers. DGA can identify potential transformer failures, which allows it to potentially prevent further damage from occurring. Mineral Oil (MO) and Rice Bran Oil (RBO) have both been used as conventional transformer oils for the purpose of this study, and a comparison of their DGA evaluations under electrical breakdown faults has been carried out. RBO has excellent oxidation stability and benefits in terms of both price and accessibility. Therefore, this study focuses on RBO as a sustainable option to petroleum-based MO for transformer oil. The many approaches developed for analyzing these gases and interpreting their significance include Key Gas, Duval Triangle and Pentagon Method, Doernenburg Ratio, Rogers Ratio, and IEC Ratio. The diagnostic approaches were not completely reliable for identifying electrical faults in RBO. The findings suggest that present DGA interpretation procedures for RBO or vegetable oil shall be properly modified. In the case of MO, however, DGA analysis indicated that there is a thermal crack in the oil sample that must be addressed.**

Keywords—mineral oil, rice bran oil, DGA, thermal, transformer

I. Introduction

Insulating oil serves as a coolant in the operation of transformer equipment and insulator between the energized parts. Petroleum-based mineral oil (MO) is the most conventional transformer oil used in power frequency and high-frequency transformers due to its physical, chemical, dielectric and electrical properties. However, the use of MO composition is a relatively low flash point and potentially starts a fire. Hence, researchers have widely investigated natural ester oil as alternative transformer oil due to its biodegradability and environmentally friendly. Biodegradable oil feature qualities such as high biodegradability (> 95%), low toxicity, high flash points (>300 °C), fire points (>300 °C), and lesser flammability [1]. The present study investigates gas characteristics of Rice Bran Oil (RBO) is extracted from the hard outer brown layer of rice known as rice husk (chaff) [2].

For many years, Dissolved Gas Analysis (DGA) has been utilised as an effective and dependable instrument for detecting incipient defects in MO. DGA research provides incredibly valuable information to asset managers in energy supply businesses. It is thus critical to verify that standard DGA analysis methodologies continue to function effectively when different oil is proposed in transformers. In this paper, the fault gases produced by MO and RBO were identified, analysed, and compared.

The most vital phase in conducting gas analysis to identify faults is accurately diagnosing the defect that created the gases. Insulation oil breaks down and releases minor amounts of gases when subjected to abnormal electrical stresses. The composition of these gases is determined by the kind of defect. The identification of particular levels of gases created in an oil-filled transformer in service is frequently the earliest accessible indicator of a defect that, if not remedied, can lead to transformer failure. For this study, the effect of electrical faults on DGA analysis in MO and RBO is diagnosed using five standard methods; Key Gas, Duval Triangle, Duval Pentagon, Doernenburg, Roger Ratio and IEC Ratio Method.

II. Extraction Methods

Two types of oil are involved, mineral oil (MO) and rice bran oil (RBO). Table I shows the list of detailed components of MO and RBO.

TABLE I. Detail Components of Mineral Oil and Rice Bran Oi

Types Of Oil	Mineral Oil (MO)	Rice Bran Oil (RBO)
Brand	Hyrax Hypertrans	Green Love
Physical Appearance	Clear and Bright	Clear
Viscosity (cSt)	10.4	37 – 50
Saturated Fat (g)	-	22.0
Mono-unsaturated Fat (g)	-	36.3
Polyunsaturated Fat (g)	-	21.2
Vitamin E (mg)	-	7.5

This work is supported by the National Defence University of Malaysia (UPNM/ 2020/ GPJKP/ TK/ 9).

2022 IEEE International Conference on Power and Energy (PECon) | 978-1-6654-0990-2/22/$31.00 ©2022 IEEE | DOI: 10.1109/PECON54459.2022.9988791

Gas chromatography (GC) analysis will be used to separate or extract the dissolved gas in tested samples. GS was selected since it is appropriate for liquid samples and has been regulated for gas extraction in transformer oil in accordance to the ASTM D3612 standard [3]. James and Martin [4] initially have been using this technique in 1952. However, after IEEE, IEC and ASTM published guidelines on how to measure and analyse DGA in transformer oil, this technique becomes more prevalent and widely recognized as the effective DGA technique for quantifying fault gases dissolved in MO. By using GC, a few individual gases can be identified including Hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_3), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen (N_2), and oxygen (O_2). Table II shows the amount of respective gas content in parts-per-million (ppm) for MO and RBO.

TABLE II. CONCENTRATION OF GASES IN MINERAL OIL AND RICE BRAN OIL

Types of Gases	Concentration of Gases (ppm)	
	Mineral Oil (MO)	Rice Bran Oil (RBO)
H_2 (Hydrogen)	1469	1231
CH_4 (Methane)	486	62
C_2H_6 (Ethane)	44	64
C_2H_4 (Ethylene)	665	217
C_2H_2 (Acetylene)	4120	2246
CO (Carbon Monoxide)	322	305

III. DGA INTERPRETATION

A. Key Gas Method

The presence of fault gases in transformer oil is defined by the temperature or energy that breaks the chemical bonds in the insulation oil, hence reducing the oil's dielectric insulation strength. The Key Gas Method (KGM) interprets fault gases extracted from the oil in accordance to the IEC standard C57.104 [5]. The presence of fault gases commonly depends on the temperature or energy that will break the chemical structure bonding of the oil samples. This approach detects faults by using individual gases rather than calculating gas ratios. The significance and amount of the gases are referred to as "key gases." The KGM addresses four categories of defects; thermal fault due to overheated oil, thermal fault due to overheated cellulose, electrical fault due to corona, and electrical fault due to arcing.

TABLE III. CONCENTRATION OF GASES IN MINERAL OIL AND RICE BRAN OIL

Types of Gases	Relative Proportion of Gases (%)	
	Mineral Oil (MO)	Rice Bran Oil (RBO)
H_2	20.67	29.84
CH_4	6.84	1.50
C_2H_6	0.62	1.55
C_2H_4	9.36	5.26
C_2H_2	57.98	54.45
CO	4.53	7.39
Total Dissolved Combustible Gas (TDGC)	7106	4125

Table III shows approximate relative proportions (%) for each fault gas. The TDGC value of mineral oil (MO) is more than 4630 ppm, which indicates an excessive decomposition as suggested by IEC 60599 [6]. Continued operating of the transformer may result in transformer failure. However, for rice bran oil (RBO), the TDGC is within 1921-4630 ppm, which indicates that there has been a significant amount of decomposition and need for a fast response to establish a trend. Referring to the individual relative proportion of combustible gases, it can be seen that C_2H_2 is the key gas for MO. For the transformer, a high relative proportion of C_2H_2 is a key sign gas for overheating problems and arc discharge due to an electrical fault [7]. An electrical arc can occur within the tank if the dielectric strength of the insulating oil in the tank deteriorates which will attribute to pollution or other factors. The arc indicates a quick release of energy that can result in insulating oil vaporisation and ionisation of the oil.

B. Duval Triangle Method

The Duval Triangle method is a graphical method that utilizes the relative percentages of the three fault gases: CH_4, C_2H_4 and C_2H_2. Figure 1 shows the conventional Duval triangle that has been subdivided into fault zones corresponding to the six basic IEC fault types; partial discharges of corona types (PD), discharges of low energy (D1), discharges of high energy (D2), thermal fault below 300°C (T1), thermal fault at 300°C (T2), thermal fault between 300°C to 700°C (T3) and combinations of thermal and electrical discharge fault (DT). The top vertex of the triangle corresponds to 100% methane (CH_4), the right bottom vertex corresponds to 100% ethylene (C_2H_4) and the left bottom corresponds to 100% acetylene (C_2H_2). The fault zone in which the point is located denotes the type of fault that is most likely to have caused that combination of gas concentrations [8], [9].

Figure 2(a) and Figure 2(b) show the indicated faults of MO and RBO using the Duval Triangle. The calculation of the relative proportion of three gases is listed as Equation (1).

$$C_T = CH_4 + C_2H_4 + C_2H_2 \quad (1)$$

$$\%\,CH_4 = 100 \times \frac{CH_4}{C_T}$$

$$\%\,C_2H_4 = 100 \times \frac{C_2H_4}{C_T}$$

$$\%\,C_2H_2 = 100 \times \frac{C_2H_2}{C_T}$$

where

C_T : total relative proportion of three gases
CH_4 : concentration of methane gas in ppm
C_2H_4 : concentration of ethylene gas in ppm
C_2H_2 : concentration of acetylene gas in ppm
$\%\,CH_4$: relative proportion of methane gas
$\%\,C_2H_4$: relative proportion of ethylene gas
$\%\,C_2H_2$: relative proportion of acetylene gas

For Mineral Oil:

$$C_T = 486 + 665 + 4120$$

$$\% \, CH_4 = 9.22 \,\%$$
$$\% \, C_2H_4 = 12.62 \,\%$$
$$\% \, C_2H_2 = 78.16 \,\%$$

For Rice Bran Oil:

$$C_T = 62 + 217 + 2246 = 2525$$

$$\% \, CH_4 = 2.46 \,\%$$
$$\% \, C_2H_4 = 8.59 \,\%$$
$$\% \, C_2H_2 = 88.95 \,\%$$

Using the Duval Triangle method, it has been observed that both MO and RBO discharged with a low energy. Low energy discharge can be caused by an electrical discharge passing through the oil, through the paper insulation, or at the surface of the paper insulation. These discharges can also be caused by a degradation of the surface of the paper insulation, which can result in the formation of conducting paths or small arcs. Low energy events, such as partial discharge that produce hydrogen and trace amounts of methane and ethane, are able to generate all the gases, including acetylene, which required the highest energy. In most cases, faults begin as incipient defects with minimal energy, but they can eventually progress into more severe faults with more energy or higher temperatures.

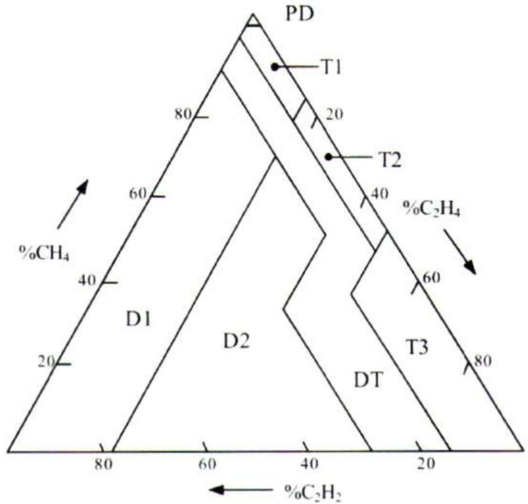
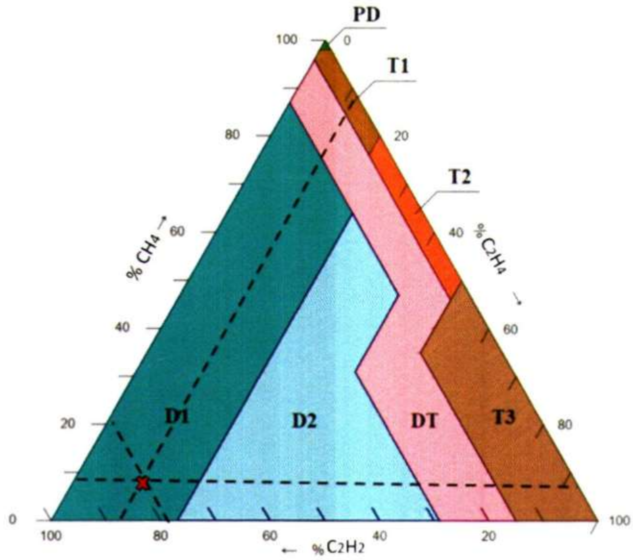
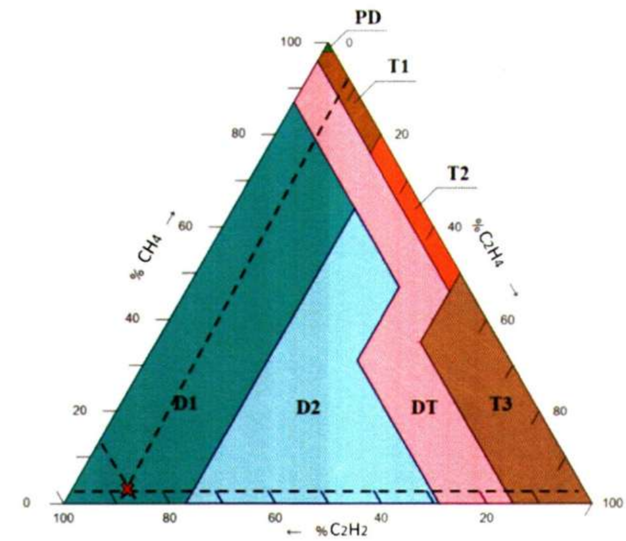


Fig. 1. Conventional Duval Triangle.



(a)



(b)

Fig. 2. Duval Triangle formed by the three axes that correspond to the relative proportion of CH_4, C_2H_2 and C_2H_4 gases in (a) Mineral Oil, and (b) Rice Bran Oil.

C. Duval Pentagon Method

The Duval Pentagon Method uses five gases to detect types of faults undergone by a transformer [10]. Figure 3 shows the representation of fault areas in the Duval Pentagon. The center of pentagon corresponds to 0% gas concentration, while the summit corresponds to 100% of gas concentration. There are five points on each axis that reflect the proportional proportion of each gas. Each of these relative proportions is plotted in the corresponding gas axis, and then forms the generic irregular polygon of five sides. For the final classification of the DGA, the geometrical centroid coordinate will be determined. To mathematically find the centroid of the irregular polygon, the coordinates of x and y need to be calculated for each individual gas shown in Equation (2). In this study, the coordinates of MO for H_2, C_2H_6, CH_4, C_2H_4, and C_2H_2 are (0, 20.67), (-0.59, 0.19), (-4.02, -5.53), (5.5, -7.57), and (55.14, 17.92). For RBO, the coordinates are (0, 7.39), (-1.47, 0.48), (-0.88, -1.21), (-1.58, -5.24) and (35.95, 15.19). Then, the geometrical centroid coordinates for MO and RBO of the Duval Pentagon that are computed using Equation (3) are (17.62, 2.68) and (3.16, 0.95) [10]. Figure 4 illustrates the irregular polygon plotted according to the coordinates and their centroid location.

$$x_{C_2H_6} = 0.62\ \% \times \cos \propto = 0.62 \times \cos 162\,^{\circ} = -0.59$$
$$x_{C_2H_6} = 0.62\ \% \times \sin \propto = 0.62 \times \sin 162^{\circ} = 0.19 \quad (2)$$

$$C_x = \frac{1}{6A}\sum_{i=0}^{4}(x_i + x_{i+1})((x_i \times y_{i+1}) - (x_{i+1} \times y_i)) \quad (3)$$

$$C_y = \frac{1}{6A}\sum_{i=0}^{4}(y_i + y_{i+1})((x_i \times y_{i+1}) - (x_{i+1} \times y_i))$$

$$A = \frac{1}{2}\sum_{i=0}^{4}(x_i \times y_{i+1} - x_{i+1} \times y_i)$$

where
x_i, y_i : coordinates of the five points of gases
C_x, C_y : coordinates of the centroid
A : surface of the polygon.

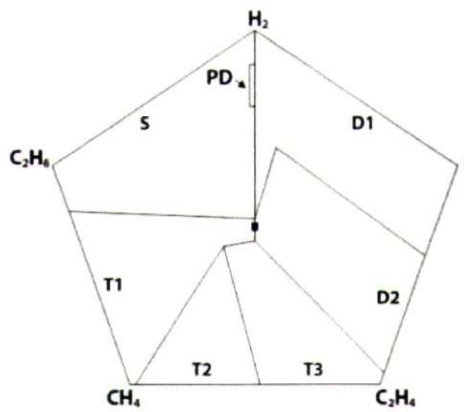
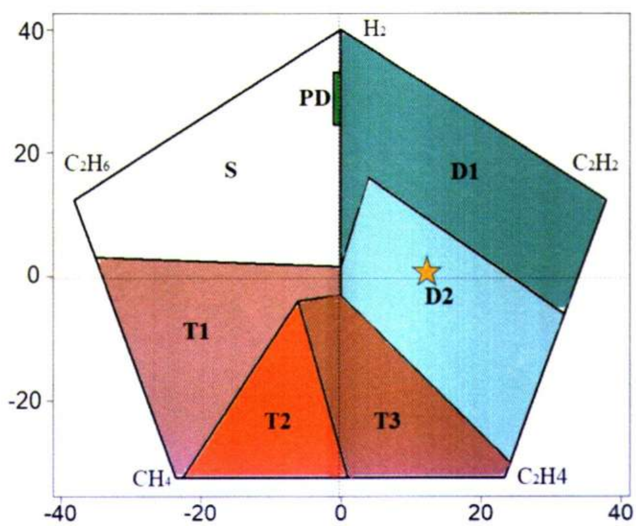
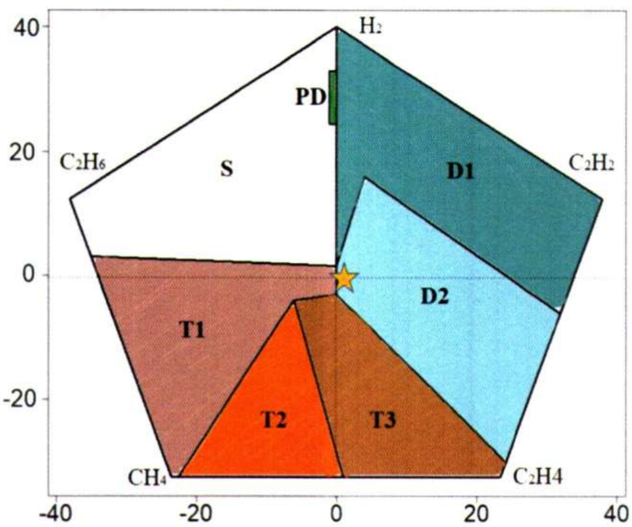


Fig. 3. Duval Pentagon for the six basic types of faults.



(a)



(b)

Fig. 4. The irregular polygon formed by five coordinates that calculated using relative proportion of H_2, C_2H_6, CH_4, C_2H_4, and C_2H_2 gases for (a) Mineral Oil and (b) Rice Bran Oil.

For both MO and RBO, it can be seen that the Duval pentagon interpretation methods provide the discharges of high energy in paper or oil, resulting in extensive damage to paper insulation or large formation of carbon particles in oil, metal fusion, tripping of the equipment and gas alarms. When the insulation of the transformer is exposed to the fault with high energy, it experiences additional stresses, which leads to the acceleration of the insulation's deterioration.

D. Doernenburg, Rogers Ratio and IEC Ratio Methods

This insulation material degradation results in the emission of several types of gases that can be used to determine the type and intensity of the stresses. To determine the condition of the transformer, concentrations of dissolved gas in oil, relative gas proportions, and gas production rates are analysed and utilised. There are many various types of ratios methods [5], and each one assigns a different combination of fault guidelines to a specific type of problem [11]. These techniques involve analysing the current gas ratios and comparing them to previously determined ratio intervals. The Doernenburg Ratio method suggests the existence of three general types of faults; thermal decomposition, corona and arcing. This method identifies faults by analysing gas concentration ratio. Each consecutive ratio is then compared with certain values as shown in Table IV to determine the validity of the four ratios. Table V lists the gas concentration ratio of MO and RBO. Rogers Ratio Method or known as Basic Gas Ratio Method is similar to Doernenburg Ratio Method, which suggests five to six general fault types via three ratios from five fault gases. Table VI shows the recommended fault diagnosis using Rogers Ratio Method, while Table VII shows the tested results of gases ratio for MO and RBO. The IEC Ratio Method both use the same three ratios as in Rogers Ratio Method but suggests different ratio ranges and interpretations. The International Electrotechnical Commission (IEC 60599) [6] fault diagnosis scheme addresses four conditions: normal ageing, partial discharge of low and high energy density, thermal faults, and electrical faults of varying intensity. Table VIII provides a list of the faults types that recommended by IEC ratio, and Table IX shows the gas concentration ratio, respectively.

TABLE IV. DOERNENBURG RATIO FAULT DIAGNOSIS

Types of Faults	Gas Ratio			
	$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{CH_4}$	$\frac{C_2H_6}{C_2H_2}$
Thermal Decomposition	> 1.0	< 0.75	< 0.3	> 0.4
Corona (low intensity PD)	< 0.1	-	< 0.3	> 0.4
Arcing (high intensity PD)	> 0.1	> 0.75	> 0.3	< 0.4

TABLE V. CONCENTRATION RATIO OF GASES IN MINERAL OIL AND RICE BRAN OIL BASED ON DOERNENBURG RATIO METHOD

Types of oil	Gas Ratio				Suggested Fault Diagnosis
	$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{CH_4}$	$\frac{C_2H_6}{C_2H_2}$	
Mineral Oil	0.331	6.195	8.477	0.011	Arcing
Rice Bran Oil	0.050	10.350	36.226	0.028	-

TABLE VI. ROGERS RATIO FAULT DIAGNOSIS

Types of Faults	Gas Ratio		
	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
Normal unit	< 0.1	> 0.1 – 1.0	< 1
Partial Discharge	< 0.1	< 1.0	< 1
Arcing	0.1 – 3.0	0.1 – 1.0	> 3.0
Low Thermal Temperature	< 0.1	> 0.1 – < 1.0	1.0 – 3.0
Thermal: < 700°C	< 0.1	> 1.0	1.0 – 3.0
Thermal: > 700°C	< 0.1	> 1.0	> 3.0

TABLE VII. CONCENTRATION RATIO OF GASES IN MINERAL OIL AND RICE BRAN OIL BASED ON ROGERS RATIO METHOD

Types of Oil	Gas Ratio			Suggested Fault Diagnosis
	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$	
Mineral Oil	6.195	0.331	15.114	-
Rice Bran Oil	10.350	0.050	3.391	-

TABLE VIII. IEC RATIO FAULT DIAGNOSIS

Types of Faults	Gas Ratio		
	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
Partial Discharge	Insignificant	< 0.1	< 0.2
Discharge of Low Energy	> 1	0.1 – 0.5	> 1
Discharge of High Energy	0.6 – 2.5	0.1 – 1	> 2
Thermal: < 300°C	Insignificant	> 1 but insignificant	< 1
Thermal: 300°C < T < 700°C	< 0.1	> 1	1 – 4
Thermal: > 700°C	< 0.2	> 1	> 4

TABLE IX. CONCENTRATION RATIO OF GASES IN MINERAL OIL AND RICE BRAN OIL BASED ON IEC RATIO METHOD

Types of Oil	Gas Ratio			Suggested Fault Diagnosis
	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$	
Mineral Oil	6.195	0.331	15.114	Discharge of low energy
Rice Bran Oil	10.350	0.050	3.391	-

The results of gas concentration ratio using the Doernenburg Method and Rogers Ratio Method have shown that both methods are inapplicable for diagnosing thermal faults in aged MO and RBO. However, IEC Ratio Method interprets that both MO and RBO produced thermal fault at low temperatures. The fact that the number of possible code combinations is greater than the number of fault sorts is one of the most significant limitations of Doernenburg ratios, Rogers ratios, and IEC ratios. Because of this, the typical outcome of these ratios is generally no decision, which is one of their important limitations [12]. Due to these constraints, either no decision will be made or a false detection will be made. A real power transformer diagnostic process will typically consider other factors, such as the variability of dissolved-gas data, the effects of loading and environmental conditions on these data, and other factors.

IV. CONCLUSION

Monitoring and diagnosing the condition of the transformer is essential in order to locate any potential faults in their early stages. The Dissolved Gas Analysis (DGA) technique is one of the most efficient methods for detecting faults in oil-filled transformers in their initial phases. In this investigation, a total of six different approaches were used to evaluate the DGA results of rice bran oil (RBO) as an alternative transformer oil in comparison to mineral oil (MO), which was the conventional oil that was affected by the electrical fault. Based on the findings, it is possible to conclude that the DGA analysis for MO is nearly consistent where arcing and low discharge of energy present in the sample. It is possible that the electric arc will cause the insulating system and the dissolved gases in the oil to degrade. Checking the gassing condition on a regular basis is something that is strongly suggested. However, in order for RBO to identify the various sorts of errors, various DGA approaches are required to be utilised. This is due to the fact that the Duval Triangle recognised a low energy discharge, the Duval Pentagon discovered a high energy discharge, and the Key Gas Method detected an arcing fault. This result is not relevant to RBO; hence, the fault prediction might be inaccurate if the same fault gas interpretation procedures are applied on RBO. In the future, new diagnostic criteria will need to be created in order to make a diagnosis.

ACKNOWLEDGMENT

The authors would like to thank the High Voltage and Sustainable Energy Group (HVSE) and the National Defence University of Malaysia (NDUM) for their guidance and support in this study.

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