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Dissolved gas analysis comparison of electrically stressed methyl ester and mineral oil

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ABSTRACT

Methyl ester is considered one of the alternative substitutes to mineral oil as an insulating liquid. This study investigates the dissolved gas analysis (DGA) of the methyl ester derived from palm oil, under low energy discharge faults. The aims are to understand the gas composition and evaluate the applicability of the well-established fault interpretation methods for mineral oil to the methyl ester. Experimental procedures were conducted based on the International Electrotechnical Commission (IEC) standards. It involved simulating electrical breakdowns in laboratory conditions as per IEC-156 standard and analyzing gas samples using gas chromatography based on IEC-567. Results show that methyl ester oils produce similar types of gases as mineral oils but at higher concentrations. The interpretation of DGA results using fault identification methods such as Duval Triangle, Duval Pentagon, and IEC ratio indicates an overestimation of fault severity in methyl ester oils, and categorizing the faults as high energy discharge. However, the key gas method correctly identifies the discharge in both methyl ester and mineral oils. These findings suggest the need for adjustments in existing DGA methods to account for the higher gas concentrations in methyl ester oils, for effective condition monitoring and maintenance of transformers if it was filled with methyl ester oil.

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1. INTRODUCTION

In power transformers, the degradation of insulation is a significant concern as it can lead to the failure of the transformer. The main causes of insulation degradation are thermal and electrical faults. These faults create gasses such as hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO) and carbon dioxide (CO_2). Dissolved Gas Analysis (DGA) is a widely accepted technique for identifying incipient faults in transformers filled with mineral oil. The analysis of gases generated by the faults provides crucial information for diagnosing the health condition of the transformer. In particular, the concentration of certain gases generated in oil, as well as their ratios, can indicate the type and the severity of fault that occurred [1]–[3].

Nowadays, natural esters-based insulating oils are increasingly popular due to their superior properties, especially in availability and environmentally friendly aspects, compared to traditional mineral oils [4], [5]. In addition, natural esters possess an advantage for their higher fire point than conventional mineral oil [6]. The oils have been widely used in distribution transformers and extend their implementation in power transformers, thus requiring proper condition monitoring and diagnosis. Research on natural ester oils has investigated dissolved gas analysis (DGA) techniques for monitoring transformers filled with the oils. Interpretation of DGA results for these oils necessitates considering their unique chemical composition, which may lead to differences in degradation pathways and gas formation compared to mineral oils. Accurate interpretation methods tailored to the specific characteristics of natural ester oils are also crucial.

Researchers have studied the DGA of natural esters under electrical faults. In study [7] reported a similar gas production of Canola oil and mineral oil under creepage discharge [7]. The natural ester produces more gases under partial discharge (PD) than the mineral oil, but both oils show a comparable production rate of gasses per unit of energy [8]. The partial discharge was correctly identified by the classical Duval Triangle and the International Electrotechnical Commission (IEC) ratio in [9]. In contrast, the creepage discharge was interpreted well by the Duval Triangle and the key gas methods in [7]. Under a lightning impulse, both oils show relatively similar gas production tendencies, except that the natural ester produces a remarkably higher amount of carbon monoxide than the mineral oil [10]. The primary gasses observed in the natural ester under a low energy arcing are hydrogen and acetylene, suggesting the possible application of the key gas method [11]. The fault was also correctly interpreted by the classical Duval Triangle method [11], [12]. Other reports show the correct diagnosis of sparking fault by the Dornenburg ratio, Rogers ratio, Duval Triangle, Muller-Schliesing-Soldner, and IEC 60599 [10], [13]. Duval Pentagon method effectively identifies and distinguishes PD, low and high energy discharge faults in Camellia oil [14]. However, quite different results are reported in study [15], where all gas ratio methods provide an unclear diagnosis of the electrical breakdown, though the Duval Triangle method does it well. It can be seen that the key gas and the Duval Triangle methods work well under partial discharge, low energy discharge, and high energy discharge. For gas ratio methods, the previous results mostly show the correct diagnosis, although few reports provide a different prediction.

Despite the research progress on the DGA in natural ester (tri-ester or triglyceride) oils, there remains a notable gap in understanding the behavior of monoester-type natural esters. Monoesters, which consist of a single fatty acid chain, represent a subset of natural ester oils with distinct chemical and physical properties. The DGA of monoesters requires more investigations to enhance our understanding of the development of more effective diagnostic tools for condition monitoring and maintenance of transformers filled with monoesters. A few results of the DGA in monoesters are reported in the literature. The monoester produces a similar type of gasses as the mineral oil does under partial discharge, but the quantity of the produced gasses is generally higher in the monoester than in the mineral oil [16]. The hydrogen production in the monoester was dominant at a higher applied voltage [17], but less quantity was observed at the lower applied voltage [16], [18]. All of these studies were conducted under the partial discharge fault. The study on the monoester under other electrical faults like low energy discharge and high energy discharge needs to be performed. This study aims to investigate the DGA of monoesters under low energy discharge. The study involves the analysis of the gases dissolved in the ester oil and the evaluation of the applicability of the fault interpretation methods that are well-established for mineral oil to the monoester, especially methyl ester. The DGA status based on the resulting data is discussed. The applicability of the existing fault interpretation methods like key gas, Duval Triangle, Duval Pentagon, and IEC ratio is evaluated.

2. METHOD

2.1. Material

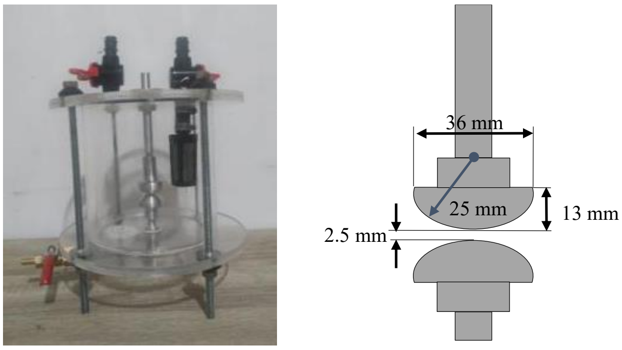
The type of monoester used in the experiment was methyl ester, derived from palm oil. It should be noted that the methyl ester was considered as one of the alternative substitutes to the mineral oil for insulating liquid purposes [19], [20]. The mineral oil was also tested for comparison. Both oil samples were used as received, similar to those in [11].

2.2. Experimental procedures

The oil chamber and the electrodes for low energy discharge simulation are shown in Figure 1. The oil sample was placed in a cylindrical chamber, which was designed similar to that in [16]. The body of the chamber was made of glass, whereas the base and the cover were made of acrylic in Figure 1(a). Differing from the former chamber design containing needle-plane electrodes for partial discharge simulation, the current design was equipped with two hemispherical electrodes with a gap of 2.5 mm for low energy discharge fault test. The schematic view of the electrode pair is shown in Figure 1(b).

The electrical fault of low energy discharge was simulated in a laboratory by performing an electrical breakdown test through electrodes paired immersed in the oil sample, based on the IEC-156 standard, as in [11], [21]. The breakdown tests were conducted many times to ensure that the generated gasses were sufficiently high to be classified as faulty conditions, which is indicated by at least status 3 of the DGA status. The identification of the DGA status will be discussed further in section 3.2. Three samples were prepared for each oil type by exposing them to electrical breakdown tests 50, 75, and 100 times. The variation of breakdown number is intended to produce different gas concentrations for evaluating the consistency of the fault identification methods under consideration. The fault identification methods are discussed in section 3.3.

An oil sample for gas analysis was taken from a small channel at the bottom of the chamber, and it was stored in a vial bottle, as shown in Figure 2(a). The samples were sent to the Laboratorium Minyak Isolasi Trafo, PT. PLN (PERSERO) Unit Induk Transmisi Jawa Bagian Tengah, Bandung, for gas chromatography analysis. The procedure was conducted based on the IEC-567 standard which is adopted by PLN as the SPLN T5.004-0: 2016. In short, the gas in oil was extracted using the headspace method, and it was conducted in a syringe, as shown in Figure 2(b). The oil sample of about 50 mL was inserted into the syringe. A space above the oil in the syringe is needed for extracted gasses, and it was created while inserting nitrogen and oxygen from ambient air. A CO_2 trap was used during the nitrogen and oxygen insertion to avoid other gasses from the air entering the syringe. The syringe containing oil was shaken for about 30 seconds three times to extract gasses in oil. The extracted gas was injected into the gas chromatography (GC) for analysis by connecting the syringe to the GC through an oil trap to avoid the oil entering the gas chromatography.



(a) (b)

Figure 1. Oil chamber for electrical breakdown test (a) the chamber's photograph and (b) electrode pairs, placed inside the chamber

(a) (b)

Figure 2. Oil samples (a) after electrical breakdown test and (b) during gas in oil extraction using syringe and CO_2 trap

3. RESULTS AND DISCUSSION

3.1. Gas composition

Figures 3, 4, and 5 show the composition of gasses detected in methyl ester and mineral oils samples after being subjected to the electrical breakdown 50, 75, and 100 times, respectively. Gasses produced by both oils are similar in type but different in quantity. All combustible gasses are produced by the methyl ester in a higher amount than the mineral oil. A similar gas pattern is also observed under PD fault in monoester [16], and in natural ester (tri-ester) [7], [8]. The similarity is due to the existence of C-H and C-C bonds in the chemical structures both oils, thus, have similar degradation mechanisms [7], [22], When a fault occurs, the discharge energy breaks the C-H and C-C bonds, forming CH3, CH2, CH, C and H radicals. Recombinations of these radicals subsequently produce Hydrogen (H-H), methane (CH3-H), ethane (CH3-CH3), ethylene (CH2-CH2), and acetylene (CH-CH) [23]. The higher gas production of the natural ester is due to the higher repetition rate of discharge in natural ester compared to the mineral oil. However, the gas concentration per energy of discharge is comparable in both oils [8]. In addition, carbon dioxide was found in a lower quantity in the methyl ester than in the mineral oil. However, combined carbon monoxide and carbon dioxide are higher in methyl ester than in mineral oil. This behavior is valid for all samples with different numbers of electrical breakdowns.

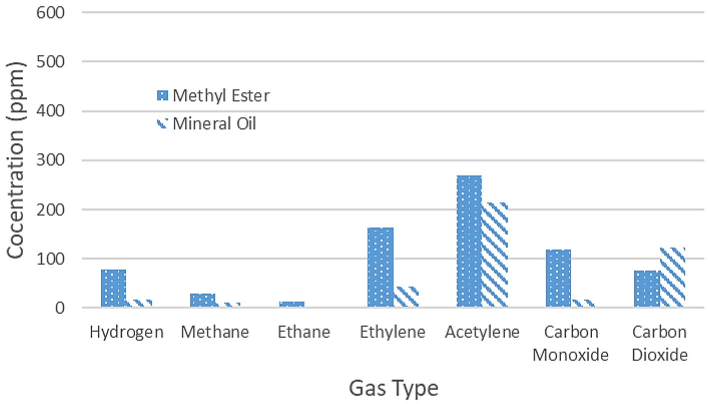


Figure 3. Gas composition in methyl ester and mineral oil samples after 50 times electrical breakdown

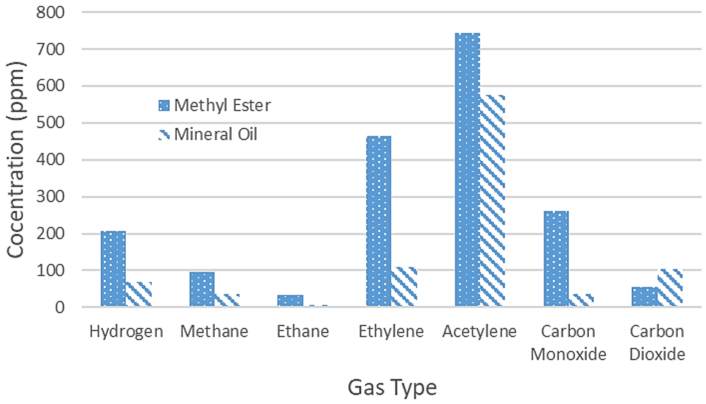


Figure 4. Gas composition in methyl ester and mineral oil samples after 75 times electrical breakdown

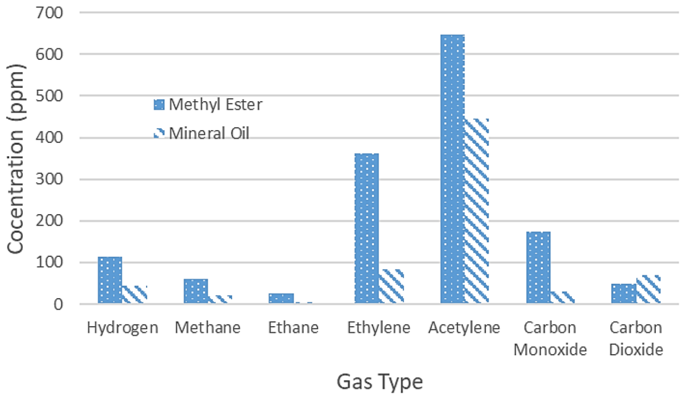


Figure 5. Gas composition in methyl ester and mineral oil samples after 100 times electrical breakdown

The pattern of observed combustible gasses in both methyl ester and mineral oils is also similar. Acetylene is the most dominant gas, followed by ethylene, carbon monoxide, hydrogen, methane, and ethane. It should be noted that carbon dioxide does not belong to the combustible gases category. However, if carbon dioxide is taken into account, then the situation is changing. Acetylene is still the most dominant gas in methyl ester, but the second-largest gas is ethylene. These tendencies are observable in all samples having different numbers of electrical breakdowns.

3.2. DGA status

IEEE provides an IEEE C57.104-2019 standard to predict the possible presence of a fault in a mineral oil-filled transformer based on DGA [24]. It uses three DGA statuses to estimate the transformer operation conditions. The DGA status 1 is related to the normal operating state of the transformer under consideration. The DGA status 2 is attributed to an abnormal condition, thus requiring more transformer monitoring. The DGA status 3 suggests the presence of a fault. Hence, it needs further actions to identify the fault type and assess the transformer. Another status for extreme DGA results (The gasses concentration or rate much higher than the limit) suggests immediate extra investigation and restriction of the transformer operation. The detailed procedure for determining the DGA status is available in [24]. It should be noted that the data presented in this paper are obtained from the simulation of the electrical fault at the laboratory scale. The gas production rate between two or more consecutive measurements is not available, and the transformer age of "unknown" is used. In addition, since the data on O_2 and N_2 concentrations are unavailable, the O_2/N_2 ratio of more than 0.2 is used, as recommended by the IEEE C57.104-2019 standard. The DGA statuses of the oil samples, that were evaluated according to the procedure given in [24], are presented in Tables 1, 2, and 3. It should be kept in mind that the DGA status 2 corresponds to the acquired concentration laid between the limit 1 and Limit 2 from the IEEE standard [24], and the DGA status 4 corresponds to the one much larger than the concentration limit 2 of the standard.

Table 1. The DGA status of methyl ester and mineral oil subjected to electrical breakdown 50 times

No	Gas	Concentration (ppm)				DGA status	
		IEEE C57.104 Limit		Methyl ester	Mineral oil	Methyl ester	Mineral oil
		Limit 1	Limit 2				
1	Hydrogen	40	90	78	17	Status 2	Status 1
2	Methane	20	50	29	11	Status 2	Status 1
3	Ethane	15	40	14	3	Status 1	Status 1
4	Ethylene	50	100	164	44	Status 3	Status 1
5	Acetylene	2	7	270	215	Status 3	Status 3
6	Carbon Monoxide	500	600	118	18	Status 1	Status 1
7	Carbon Dioxide	5000	7000	76	122	Status 1	Status 1
	Final DGA status					Status 3	Status 3

Table 2. The DGA status of methyl ester and mineral oil subjected to the electrical breakdown 75 times

No	Gas	Concentration (ppm)				DGA status	
		IEEE C57.104 Limit		Methyl ester	Mineral oil	Methyl ester	Mineral oil
		Limit 1	Limit 2				
1	Hydrogen	40	90	208	69	Status 3	Status 2
2	Methane	20	50	97	35	Status 3	Status 2
3	Ethane	15	40	34	6	Status 2	Status 1
4	Ethylene	50	100	464	110	Status 3	Status 3
5	Acetylene	2	7	742	575	Status 3	Status 3
6	Carbon Monoxide	500	600	260	122	Status 1	Status 1
7	Carbon Dioxide	5000	7000	76	917	Status 1	Status 1
	Final DGA status					Status 3	Status 3

Table 3. The DGA status of methyl ester and mineral oil subjected to the electrical breakdown 100 times

No	Gas	Concentration (ppm)				DGA status	
		IEEE C57.104 Limit		Methyl ester	Mineral oil	Methyl ester	Mineral oil
		Limit 1	Limit 2				
1	Hydrogen	40	90	114	43	Status 3	Status 2
2	Methane	20	50	60	20	Status 3	Status 2
3	Ethane	15	40	25	4	Status 2	Status 1
4	Ethylene	50	100	361	83	Status 3	Status 3
5	Acetylene	2	7	648	445	Status 3	Status 3
6	Carbon Monoxide	500	600	173	29	Status 1	Status 1
7	Carbon Dioxide	5000	7000	48	70	Status 1	Status 1
	Final DGA status					Status 3	Status 3

It can be perceived from Tables 1, 2, and 3 that the methyl ester and the mineral oil stressed by the electrical breakdown result in a similar DGA status, namely status 3. However, the methyl ester suffers more severe stresses than the mineral oil-this is valid for all oil samples stressed with different numbers of electrical breakdowns. It can be seen, in Table 1, for instance, hydrogen, methane, and ethylene in methyl ester reach DGA statuses 2, 2, and 3, respectively, whereas, those gasses only reach DGA status 1 in mineral oil. The conclusion on the final DGA status is made based on the highest status reached by any individual gas, which, in all cases, is achieved by acetylene.

3.3. Fault identification

3.3.1. Key gas method

Fault identification by the key gas method uses a specific gas having a dominant concentration among other combustible gasses. Acetylene having a concentration of equal or more than 30% is related to the fault of the arcing type. Hydrogen with a concentration equal to or larger than 85% is typical gas generation due to the partial discharge. Ethylene concentration of more than 63%, accompanied by hydrogen of about 20%, is considered due to the overheating of oil [12]. The generation of carbon monoxide up to the concentration of 92% is attributed to the overheating of cellulose [25]. The relative percentage of each gas to the total combustible gases in oil samples stressed by the electrical breakdown 50, 75, and 100 times are shown in Figures 6, 7, and 8, respectively. It is seen in all Figures that the relative percentage of acetylene in methyl ester and mineral oil are equal to or greater than 40% and 69%, respectively, which can be interpreted as gas generation due to the arcing or electrical discharge in oil [12]. These results suggest the applicability of the key gas method to the methyl ester and the mineral oil under electrical discharge conditions. Similar results are also observed in natural ester of tri-ester type, as mentioned in the literature [7], [11], [12], [14]. Thus, the difference in chemical structure between monoester (methyl ester) and tri-ester does not affect the fault identification by the key gas method to both oils under low energy discharge fault.

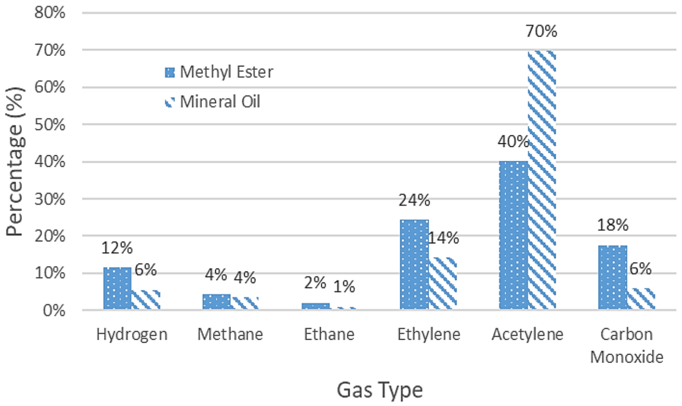


Figure 6. The relative percentage of individual gas to the total combustible gasses in methyl ester and mineral oil after 50 times electrical breakdown

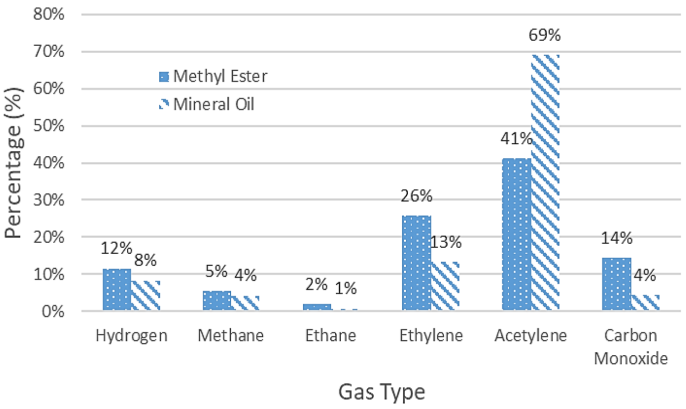


Figure 7. The relative percentage of individual gas to the total combustible gasses in methyl ester and mineral oil after 75 times electrical breakdown

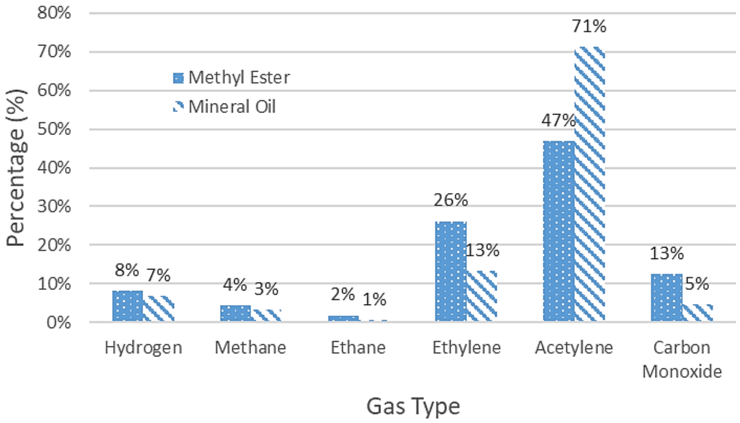


Figure 8. The relative percentage of individual gas to the total combustible gasses in methyl ester and mineral oil after 100 times electrical breakdown

3.3.2. Duval triangle method

Three kinds of gasses are used in the identification of a fault by the Duval Triangle method. The gasses are methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2). The percentage of each gas concentration to the total concentration of three gasses is calculated and plotted on three sides of a triangle (Duval Triangle). The final interpretation is determined graphically at the intersection of three lines drawn from each side of the triangle [26]. The interpretation result is categorized as thermal fault having a temperature below 300 °C (T_1), thermal fault with a temperature between 300 °C and 700 °C (T_2), thermal fault with a temperature above 700 °C (T_3), partial discharge (PD), low energy discharge (D_1), high energy discharge (D_2), and the combination of electrical and thermal faults (DT).

Tables 4, 5, and 6 tabulate the percentage concentration of gases in both oil samples stressed by the electrical breakdowns, 50, 75, and 100 times, respectively. In Table 4, for instance, the methane, ethylene, and acetylene concentrations in methyl ester stressed by electrical breakdown 50 times are 29, 167, and 270 ppm, respectively. The relative percentage of concentration of each gas is 6%, 35%, and 38%, respectively. The resulting interpretation is represented by the blue circle mark in the Duval Triangle shown in Figure 9. Other cases are calculated and are determined similarly. The mineral oil samples (triangles) are correctly interpreted as experiencing discharge of low energy (D_1), whereas the methyl ester samples (circles) are diagnosed as suffering discharge of high energy (D_2). The method overestimates the severity of fault in methyl ester. This behavior might be related to the higher repetition rate of discharge in esters compared to that in mineral oil [8], [16]. The difference in electrical discharge behavior, thus gas production between natural esters and mineral oil is due to the chemical composition difference [27]. The natural esters have lower ionization energy and a larger dipole moment, which makes the natural ester more likely to ionize and produce electrons, and promotes the formation of electron avalanches and streamers. The discharge in liquid is also affected by the presence of water. Natural esters typically have higher affinity to the water compared to the mineral oil [28], [29].

Table 4. The percentage of individual gas in methyl ester after 50 times electrical breakdowns

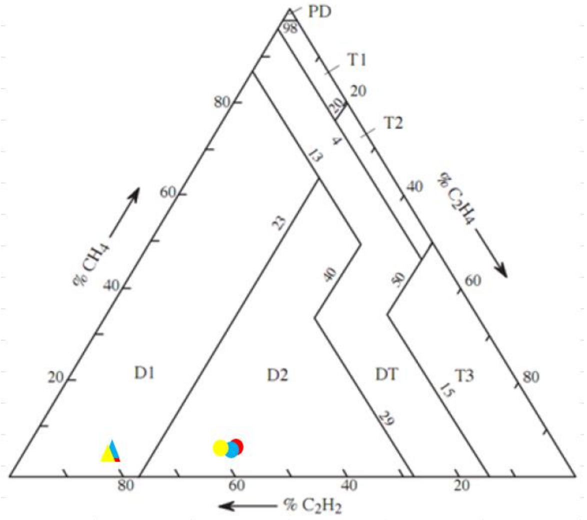
No	Gas type	Gas percentage in-	
		Methyl ester	Mineral oil
1	Methane	6%	4%
2	Ethylene	35%	16%
3	Acetylene	58%	80%

Table 5. The percentage of individual gas in methyl ester after 75 electrical breakdowns

No	Gas type	Gas percentage in-	
		Methyl ester	Mineral oil
1	Methane	7%	5%
2	Ethylene	36%	15%
3	Acetylene	57%	80%

Table 6. The percentage of individual gas in methyl ester after 100 times electrical breakdowns

No	Gas type	Gas percentage in-	
		Methyl ester	Mineral oil
1	Methane	6%	4%
2	Ethylene	34%	15%
3	Acetylene	61%	81%



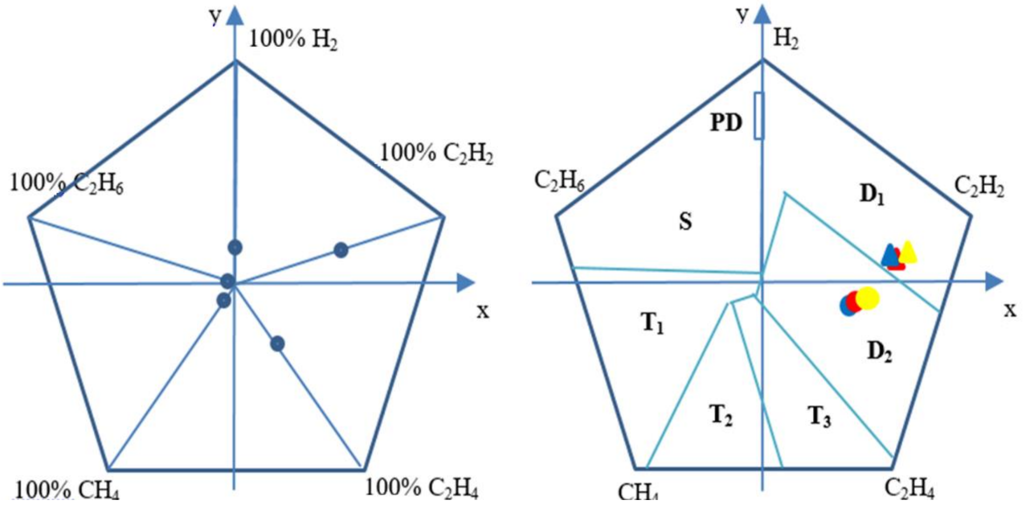
Circle	Methyl ester
Triangle	Mineral oil
Red	50 times discharge
Blue	75 times discharge
Yellow	100 times discharge

Figure 9. Duval Triangle and the fault identification in methyl ester and mineral oil stressed by the electrical breakdown 50, 75, and 100 times

3.3.3. Duval pentagon method

The Duval Pentagon method utilizes two kinds of pentagons in interpreting a fault. The technique uses five types of gasses, namely, hydrogen (H_2), ethane (C_2H_6), methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2) in Figure 10. In the first pentagon, the percentage of concentration of each gas to the total concentration of five gasses is first calculated. It is followed by calculating the two-dimensional Cartesian coordinate of each gas. A line is drawn from the center to each angle of the pentagon, representing the axis of each gas, on which the resulting concentration percentage is plotted in Figure 10(a). It should be noticed that the axes of acetylene and ethylene form angles of 18° and -54° to the positive side of the x-axis of the Cartesian coordinate, respectively, whereas the axes of ethane and methane form angles of, respectively, -18° and 54° to the negative side one. The hydrogen axis is in parallel with the y-axis. Once all gasses coordinates of an oil sample are obtained, the centroid of those five coordinates is calculated and plotted in another Pentagon to interpret the type of fault in Figure 10(b). S in the figure is related to the stray gases. The detailed calculation and representation of the centroid are available in [30].

For methyl ester stressed by the electrical breakdown 50 times, the oil produced hydrogen, ethane, methane, ethylene, and acetylene with concentrations of 78, 14, 29, 164, and 270 ppm, respectively. The correlated percentages of the individual gasses are 14.1%, 2.5%, 5.2%, 29.6%, and 48.7%, respectively. The plots of all separate gasses are shown in Figure 10(a). The calculated coordinate of the centroid is (19.0, -3.4), represented by the red circle mark shown in Figure 10(b). It should be noticed that the maximum axis of all gasses in Figure 10(b) is 40%. All cases are calculated and represented similarly. Their results are plotted in Figure 10(b). For methyl ester, all three samples result in the centroids (circles) located in the D_2 region of the pentagon, the region dedicated to the fault of high energy discharge. All results are consistent with those obtained by the Duval Triangle method. For mineral oil, all samples result in the centroids (triangles) located in the D_1 area, the area of the low energy discharge, which is also consistent with the Duval Triangle method results. The Duval Pentagon method is an improved version of the Duval Triangle method [31], it is reasonable that both methods show similar results.



(a) (b)

Figure 10. The Duval Pentagon, (a) example representation of gasses concentration percentages in methyl ester stressed 50 times and (b) centroids plots of gasses coordinates of oil samples

3.3.4. IEC 599 ratio method

This method uses three kinds of gas ratios to identify a fault. The ratios are C_2H_2/ C_2H_4, CH_4/H_2, and C_2H_2/C_2H_4. The fault type is estimated using a set of predefined limits of such gas ratios, as shown in Table 7 [32]. NS in the table means whatever the value, it does not substantially affect the diagnosis result.

The faults identified by the IEC 599 method are depicted in Table 8. The method overestimates the electrical faults in all methyl ester samples as the high energy discharge (D_2). The results agree with the Duval Triangle and the Duval Pentagon methods. The method also correctly identifies the electrical fault in mineral oil stressed 75 times as the low energy discharge (D_1) but gives an unclear identification in mineral oil stressed 50 and 100 times. The method cannot judge D_1 since their CH_4/H_2 ratios, 0.64 and 0.51, are outside the range of 0.1–0.5. Conversely, they cannot be considered D_2 since their C_2H_2/C_2H_4 ratios, 4.89 and 5.36, are outside the range limit of 0.6–2.5. However, the results are closer to the D_1 than to the D_2. This unclear identification is due to the overlap fault zone or the gas ratio drops outside the determined range [31].

Table 7. Fault identification according to the IEC 559 ratio method

No	Nature of fault	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
1	Partial discharge (PD)	NS	<0.1	<0.2
2	Discharge of low energy (D_1)	>1	0.1–0.5	>1
3	Discharge of high energy (D_2)	0.6–2.5	0.1–1	>2
4	The thermal fault of low temp. (T_1)	NS	>1	<1
5	The thermal fault of medium temp. (T_2)	<0.1	>1	1–4
6	The thermal fault of high temp. (T_3)	0.2	>1	>4

Table 8. The results of fault identification based on the IEC 559 Ratio method

No	Oil sample, number of breakdowns	Ratio of concentration			Identified fault
		C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	
1	Methyl ester, 50 times	1.6	0.4	11.7	D_2
2	Methyl ester, 75 times	1.6	0.5	13.6	D_2
3	Methyl ester, 100 times	1.8	0.5	14.4	D_2
4	Mineral oil, 50 times	4.9	0.6	14.7	D_1^*
5	Mineral oil, 75 times	5.2	0.5	18.3	D_1
6	Mineral oil, 100 times	5.4	0.5	20.8	D_1

4. CONCLUSION

The DGA comparison of methyl ester and mineral oil under electrical breakdown has been made, and the applicability of the fault identification methods has been evaluated. It is found that methyl ester and mineral oils produce similar gas types, but methyl ester generates a relatively higher concentration of the gasses than mineral oil does. Consequently, fault identification methods like the Duval Triangle, the Duval Pentagon, and the IEC 599 methods overestimate the fault in all methyl ester samples by categorizing the fault as the discharge of high energy. On the other side, all methods correctly identify the discharge of low energy in the mineral oil. The key gas method also correctly identifies the electrical discharge in all samples of both oils. The fact that ester tends to generate a higher concentration of gasses than mineral oil under electrical discharge, then the concentration of generated gasses per discharge energy could be a reasonable adjustment to the existing DGA method for the proper application in the methyl ester oil, which requires further investigation.

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