Investigating High Intensity Thermal Faults in Ester-Based Transformer Oil: A Dissolved Gas Analysis Approach

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ABSTRACT

Dissolved Gas Analysis (DGA) is a significant diagnostic tool for assessing transformer conditions, especially for detecting thermal faults. These faults, stemming from heightened thermal and electrical stresses on liquid insulation and cellulosic materials, generate various gases dissolved in oil. With the rise of environmental concerns, ester-based liquid insulation, like natural and synthetic esters, is an alternative to Mineral Oil (MO) in transformers. However, interpreting DGA data for ester-based oils requires an understanding of the distinct fault gas profiles they exhibit. In the current study, high intensity thermal faults were generated and analyzed by DGA in three different types of transformer oils: MO, natural ester, and synthetic ester, utilizing a novel method of inducing/which induces high intensity thermal stress. The results revealed differences in fault gas generation and concentrations among the three oil types, highlighting the importance of tailored interpretation methods. Since standard DGA interpretation methods are not available for ester filled transformers, these results were validated using established DGA interpretation techniques of MOs. While traditional methods may not fully capture fault conditions in natural and synthetic esters, the present study proposes Duval Triangles and Pentagons for accurate interpretation, shedding light on fault types and their implications for transformer health. The critical role of DGA in assessing transformer health is underscored, particularly in the context of evolving insulation technologies towards a greener future.

Keywords-Dissolved Gas Analysis (DGA); thermal fault; natural ester; synthetic ester; interpretation techniques; duval triangles and pentagons

I. INTRODUCTION

The safe operation of power transformers is crucial in power supply and distribution systems. The breakdown of transformers can be attributed to several causes. One of them is thermal stress, where excessive heat can degrade the insulating materials and lead to overheating. Thermal aging, resulting from prolonged exposure to high temperatures, further deteriorates insulation, reducing the transformer's efficiency and lifespan [1-3]. Electrical arcing is another significant factor that can cause localized overheating and the formation of conductive paths that can lead to short circuits [4, 5]. Mechanical stress, often due to vibrations or physical impacts, can damage internal components and insulation. Moisture ingress can also compromise insulation effectiveness and accelerate the aging process [6]. Additionally, chemical contamination from the environment or internal reactions can corrode parts and degrade insulation materials. Thermal faults in transformers pose a significant risk to the reliable operation of power distribution systems [6]. These faults can result from various factors, such as overloading, short circuits, inadequate cooling, aging of the insulation materials, and adverse environmental conditions. Overloading occurs when the transformer exceeds its rated capacity, leading to excessive heat generation in winding and insulation materials, while short circuits cause intense heat due to rapid high-current flow, creating localized hot spots. Insufficient cooling or poor ventilation exacerbates the temperature rise, further increasing the likelihood of thermal faults. Aged insulation materials exhibit low capability of withstanding heat over time, making transformers more vulnerable to thermal failures. Additionally, harsh environmental conditions, including extreme temperatures, contribute to the development of thermal faults [7, 8].

To mitigate these risks, preventive measures such as regular maintenance, monitoring of operating conditions, and proper cooling system designs are crucial. Deploying thermal protection devices, like temperature sensors and alarms, facilitates the prompt detection of abnormal temperature rises, enabling timely intervention to prevent equipment damage or failure. Furthermore, DGA enables detecting thermal faults in transformers [9, 10]. It is employed for evaluating the condition of transformers. Its effectiveness has been proven through practical experience. In DGA, the concentrations of various gases are measured, including hydrogen (H_2), methane (CH_4), ethane (C_2H_6), acetylene (C_2H_2), ethylene (C_2H_4), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen (N_2), and oxygen (O_2). During incipient fault conditions, these gases are dissolved in the oil well before any free gas accumulates in the gas relay. The specific combination of gases generated in the oil is dependent on the nature of the fault and is linked to the energy level and temperature at the fault location [11, 12]. By analyzing the oil sample for its dissolved gas content, potential thermal faults can be detected early, allowing for the implementation of proactive maintenance measures. Optimizing transformer loading and implementing effective cooling strategies are additional measures that can enhance thermal performance and extend equipment lifespan, thereby reducing the likelihood of thermal faults and minimizing downtime in power distribution systems [13].

The historical effectiveness of DGA in interpreting transformer conditions is attributed to the extensive data and experience with MO-based transformers. Ester-based liquid insulation, encompassing Natural Ester Oil (NEO) and Synthetic Ester Oil (SEO), is a practical alternative to MO, driven by environmental and safety considerations [14, 15]. NEO, sourced from renewable organic materials, boasts benefits like biodegradability, heightened fire safety, substantial moisture saturation capacity, and prolonged cellulosic insulation life. The contributions of natural ester-based liquid insulation lie in environmental friendliness and proven longevity enhancement for the insulation system [16, 17]. However, the adoption of NEO and SEO introduces a challenge due to the lack of specific data and experience. This scarcity creates uncertainty in the interpretation of DGA results. To bolster the reliability of fault identification in transformers using NEO, more comprehensive data and practical experience are required. Gaining deeper insights into the dissolved gas patterns linked to ester oil transformers will significantly refine the DGA interpretation methods and promote reliable fault detection [18].

This study investigates the gas generation during thermal faults conducted on NEO and SEO and compared to MO as a benchmark. The thermal faults were simulated by applying a high current through a heating element immersed in the oil under study. The fault gases emitted from the oil under investigation were quantified using DGA, and the data were interpreted utilizing the key gas, Doernenburg ratio, Rogers ratio, IEC ratio, Duval triangle, and Duval Pentagon methods.

II. EXPERIMENTAL PART

In this study, various oils commonly utilized in power transformers were selected, including an uninhibited MO, a soybean-based NEO, and an SEO, all readily available in the market. Table I lists the essential physical, chemical, and electrical characteristics of these three oils.

TABLE I. PHYSICAL, CHEMICAL, AND ELECTRICAL PROPERTIES OF THE DIFFERENT INSULATING OILS

Parameter	MO	NEO	SEO
Appearance	Transparent	Light green	Transparent
Density at 20 ℃ (kgm^{-3})	826	920	970
Viscosity at 40 ℃ (mm^2s^{-1})	9.7	32.4	29.3
Acidity (mg KOH/g of oil)	0.0016	0.03	0.03
Breakdown voltage (kV)	70.6	71.4	75
tan δ at 90 ℃	0.0004	0.0014	0.0081
Pour point (℃)	-48	-18	-56
Flash point (℃)	158	326	260

A. Thermal Fault Generation Setup

Thermal faults are categorized into three groups based on the temperature ranges of faults: T1 (t < 300 °C), T2 (300 °C < t < 700 °C), and T3 (t > 700 °C) [19]. To simulate high-intensity thermal faults (T3) in transformers and analyze the proportions of dissolved gases in different types of insulating oils under the same fault conditions, thermal tests were conducted within the oil medium only. Thermal faults corresponding to T3, where the temperature exceeds 700 °C, were simulated within a 1.2-L airtight glass chamber equipped with current-carrying wires and copper rods connected to a heating element. Approximately 800 ml of oil was filled in the glass chamber. Kanthal A-1 grade wire coil was chosen as the heating element due to its high resistance and melting point of up to 1400 °C. Kanthal A-1 is an alloy metal with iron, aluminum, and chromium that works well at high temperatures. The thermocouple was tightly wound around the coil to measure the temperature of the heating element. O-rings were used to seal all connections to ensure gas tightness of the system. As shown in Figure 1, the entire arrangement was placed on a magnetic stirrer plate to ensure constant stirring and oil heat dissipation. A current source was used to control the temperature of the heating element and the thermocouple was employed to monitor the temperature. The oil samples were removed from the upper glass chamber utilizing a syringe-connected pipe in order to measure the dissolved gas.

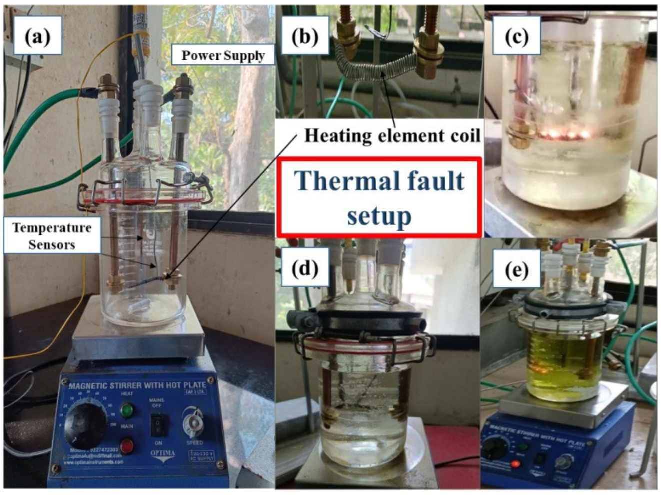

Fig. 1. (a) Thermal fault generation set up, (b) heating element coil, (c) thermal fault in MO, (d) thermal fault in SEO, and (e) thermal fault in NEO.

B. *Thermal Fault Cycling Program*

The experimental procedure, depicted in Figure 2, commenced with the measurement of the initial dissolved gas content of all oils using gas chromatography, denoted as S0.

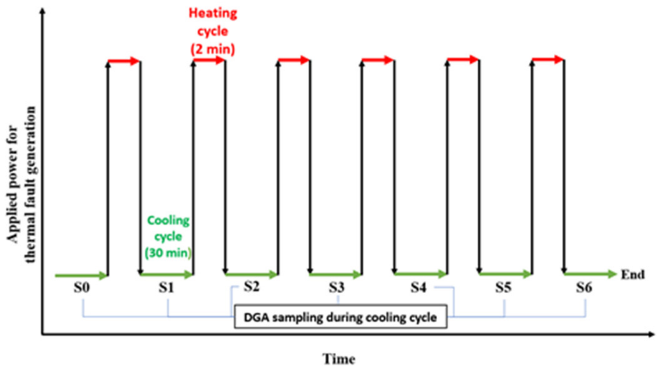

Fig. 2. Cycling procedure during the thermal fault generation.

Subsequently, a power of 1100 W was applied to heat the heating element until it turned red hot for a duration of 2 min, reaching a temperature above 800 °C. Subsequently, the oil was allowed to cool for 30 min, after which DGA was conducted. This sequence of heating, cooling, and DGA was repeated six times, with each successive DGA measurement labeled as S1, S2, S3, S4, S5, and S6. For mineral insulating oils, numerous established interpretation methods for DGA exist, supported by various real case studies, which are not available for NEO and SEO. Consequently, the experimental procedure for generating the high-temperature thermal fault T3 was validated using the MO as a reference. The same experimental conditions were applied to NEO and SEO and different interpretation methods were utilized to compare the gases formed under the simulated thermal fault conditions.

III. RESULTS AND DISCUSSION

The dissolved gas concentrations for all the three types of insulating oils MO, NEO, and SEO, were measured using the space method with the gas chromatographic technique, following the IEC 60567.

Figure 3 displays the different dissolved gas concentrations in ppm for all the three types of oils, generated under high temperature thermal fault (T3) conditions. As portrayed in Figure 3, MO generated less H_2 during the T3 fault compared to NEO and SEO. However, the generated CH_4, C_2H_2, and C_3H_6 showed similar behavior in all three oil types. The generation of C_2H_4 in NEO was initially high. However, with the continuous application of energy, the increase rate in C_2H_4 was lower. In contrast, the rate of C_2H_4 generation in SEO increased as the thermal faults increased. C_2H_6 was additionally generated in high amounts in the NEO. The amount of C_2H_6 was low in MO and SEO. Finally, the generation of C_3H_6 was similar for all three oil types.

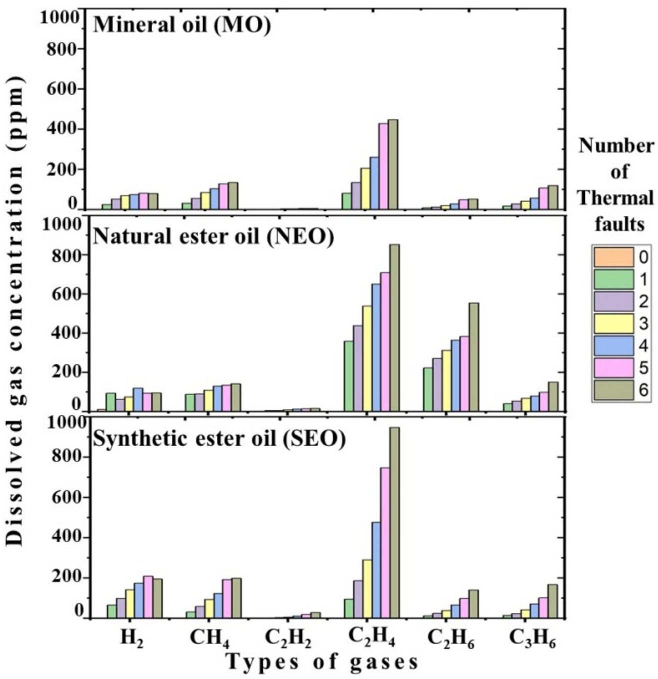

Fig. 3. Graphical representation of the gases generated from each oil sample.

To evaluate the applicability of the five DGA interpretation methods (Doernenburg ratio, Roger ratio, IEC 60599 basic gas ratio, Duval triangles, and Duval pentagons), all three types of oils were subjected to a laboratory-developed thermal fault setup. The MO was considered the base for validating the setup suitability. Table II shows the different gas ratio values based on various interpretation methods. Furthermore, all interpretation methods are discussed in depth.

TABLE II. EVALUATED GAS RATIOS AS PER VARIOUS DIAGNOSTIC METHODS FOR MO, NEO, AND SEO AT VARIOUS THERMAL FAULT (T3) CYCLES

Gas ratios		R1 CH_4/H_2	R2 C_2H_2/C_2H_4	R3 C_2H_2/CH_4	R4 C_2H_6/C_2H_2	R5 C_2H_4/C_2H_6
MO	1	1.27	0.02	0.06	4.50	9.11
	2	1.08	0.01	0.04	7.00	9.64
	3	1.21	0.02	0.06	4.20	9.86
	4	1.39	0.02	0.05	5.80	9.03
	5	1.57	0.02	0.05	7.00	8.76
	6	1.67	0.02	0.05	7.57	8.45
NEO	1	0.95	0.02	0.07	37.33	1.60
	2	1.42	0.01	0.07	45.33	1.61
	3	1.47	0.02	0.09	31.40	1.72
	4	1.09	0.02	0.10	28.08	1.78
	5	1.44	0.02	0.11	25.60	1.85
	6	1.48	0.02	0.11	34.63	1.54
SEO	1	0.48	0.01	0.03	13.00	7.38
	2	0.59	0.02	0.07	6.25	7.48
	3	0.66	0.02	0.06	6.67	7.28
	4	0.70	0.03	0.10	5.58	7.12
	5	0.92	0.03	0.10	4.95	7.56
	6	1.02	0.03	0.15	4.86	6.72

A. Doernenburg Ratios for Key Gases

The Doernenburg ratio method was first described in 1974 [20]. This method utilizes the ratios R1, R2, R3, and R4, as shown in Table III. The Doernenburg method suggests the existence of three general fault types [13]. The MO and NEO satisfied all the conditions for the Doernenburg method, since thermal decomposition was established. However, the SEO does not satisfy ratio R1 in all thermal fault cycles except for the 6th one. In the case of SEO under thermal fault conditions, the CH_4 and H_2 gas concentrations were higher than those of MO. However, the R1 ratio does not confirm the existence of a thermal fault for SEO.

TABLE III. DOERNENBURG RATIOS FOR KEY GASES [13]

Proposed fault diagnosis	R1 CH_4/H_2	R2 C_2H_2/C_2H_4	R3 C_2H_2/CH_4	R4 C_2H_6/C_2H_2
	Extracted from			
	Oil	Gas space	Oil	Gas space
Thermal decomposition	>1.0	>0.1	<0.75	<1.0
Partial discharge	<0.1	<0.01	Not significant	<0.3
Arcing	>0.1 to <1.0	>0.01 to <0.1	>0.75	>1.0

B. Rogers Ratio Method

The Rogers ratio method is also utilized in the same way as the Doernenburg ratio method, but instead of using four gas ratios, as shown in Table III, three gas ratios (R1, R2, and R5) are employed, indicating five different types (cases) of faults. According to the Rogers ratio method, MO confirms the high-temperature (>700 °C) thermal fault, as observed in case 5 in Table IV. This also validates that the prepared thermal setup can generate high intensity thermal faults. Under similar conditions, NEO and SEO did not follow the Rogers ratio method and failed to confirm all the gas ratio criteria outlined in Table IV. As illustrated in Figures 4 and 5, NEO does not follow the ratio R5, and SEO does not conform to the ratio R1. This suggests that ester-based fluids do not follow the Rogers ratio method in the case of high-temperature thermal faults.

TABLE IV. ROGERS RATIOS FOR KEY GASES [13]

Case	R2 C_2H_2/C_2H_4	R1 CH_4/H_2	R5 C_2H_4/C_2H_6	Proposed fault diagnosis
0	<0.1	>0.1 to <1.0	<1.0	Unit normal
1	<0.1	<0.1	<1.0	Low energy density Arcing
2	0.1 to 3.0	0.1 to 1.0	>3.0	Arcing-high energy discharge
3	<0.1	>0.1 to <1.0	1.0 to 3.0	Low temperature thermal fault
4	<0.1	>1.0	1.0 to 3.0	Thermal fault < 700 °C
5	<0.1	>1.0	>3.0	Thermal fault > 700 °C

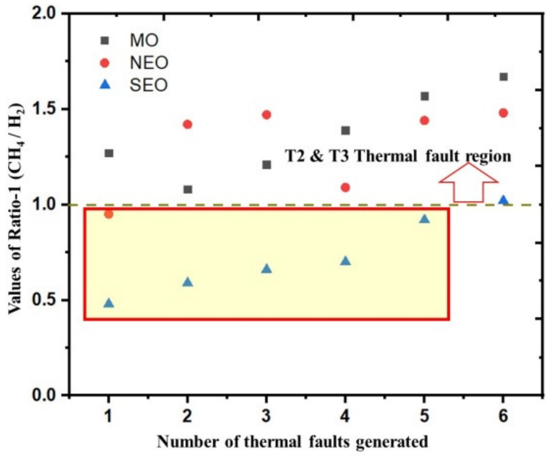

Fig. 4. Graphical representation of gas ratio R1 for the number of thermal faults generated.

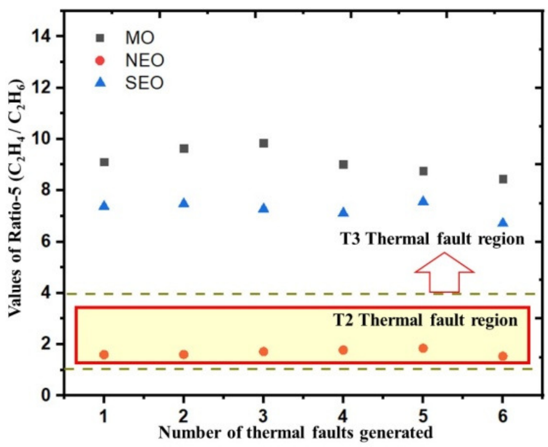

Fig. 5. Graphical representation of gas ratio R5 for the number of thermal faults generated.

C. IEC 60599 Basic Gas Ratio Method

The IEC 60599 basic gas ratio method also uses the same three gas ratios R1, R2, and R5 as the Rogers ratio method, but suggests different ratio ranges and interpretations, as shown in Table V.

TABLE V. IEC BASIC GAS RATIO METHOD [13]

Notation for fault	Fault description	R2 C_2H_2/C_2H_4	R1 CH_4/H_2	R5 C_2H_4/C_2H_6
PD	Partial discharges	NS	<0.1	<0.2
D1	Discharges of low energy	>1	0.1-0.5	>1
D2	Discharges of high energy	0.6 to 2.5	0.1 to 1.0	>2
T1	Thermal fault T< 300 °C	NS	>1 but NS	<1
T2	Thermal fault 300 °C < T<700 °C	<0.1	>1	1-4
T3	Thermal fault T> 700 °C	<0.2	>1	>4

NS = non-significant whatever the value.

According to the IEC 60599 basic gas ratio method analysis, the MO confirmed the high-temperature (>700 °C) thermal fault T3. This also validates that the prepared thermal setup can generate high intensity thermal fault T3. Under similar conditions, NEO and SEO did not follow the IEC 60599 basic gas ratio method and failed to confirm all gas ratio criteria provided in Table V. NEO does not confirm ratio R5 and SEO does not confirm ratio R1. The observations of ratios R1 and R5 were the same as those discussed in the Rogers ratio method, indicating that ester-based fluids do not follow the IEC 60599 basic gas ratio method in the case of high-temperature T3 thermal faults.

D. Duval Triangle Method

The Duval triangle method was developed from the IEC TC10 databases and the existing IEC 60599 ratio method [19]. Duval Triangle 1 uses three gases corresponding to the increasing energy content or temperature of faults. Methane is utilized for low-energy/temperature faults, ethylene for high-temperature faults, and acetylene for very high-energy/temperature/arcing faults. The relative percentages of the three gases were plotted on each side of the triangle. Duval Triangle 1 allows the identification of 6 basic types of faults, T3, T2, T1, D2, D1, and PD plus mixtures of electrical/thermal faults in zone D+T. When high or very high-temperature faults are identified using the Duval triangle 1 (T2 or T3), more information can be obtained on these faults with triangle 5, allowing the distinction between high-temperature faults T3 or T2 in oil only of lesser concern in transformers. As shown in Figures 6 and 7, all three oil types exhibited a high-temperature thermal fault T3 when subjected to high-intensity thermal stress. The Duval triangle is a highly effective interpretation method in the case of thermal fault T3. All 6 cycled DGA measurement points were seen in same T3 region in Duval triangle 1. The Duval triangle 5 also confirmed the thermal fault of T3. However, in the case of NEO, the T3 region was shifted to another part of triangle 5, as presented in Figure 7.

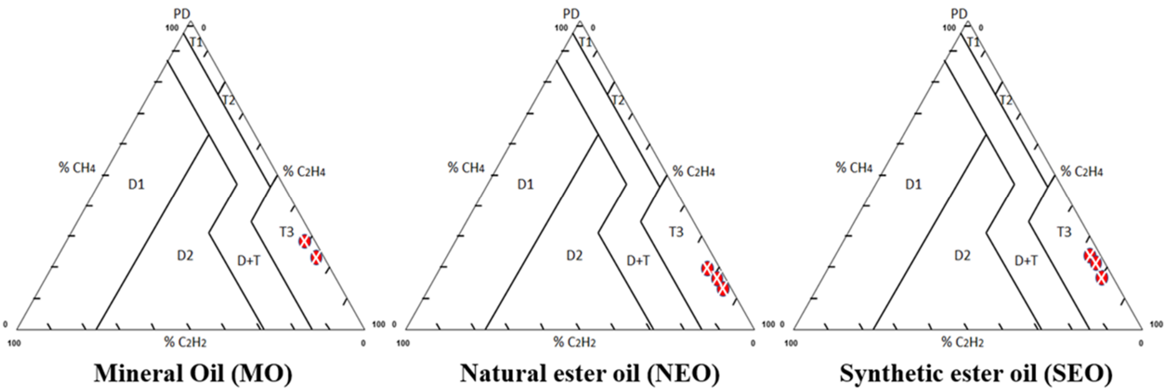

Fig. 6. Thermal fault positions in Duval triangle 1 for MO, NEO, and SEO.

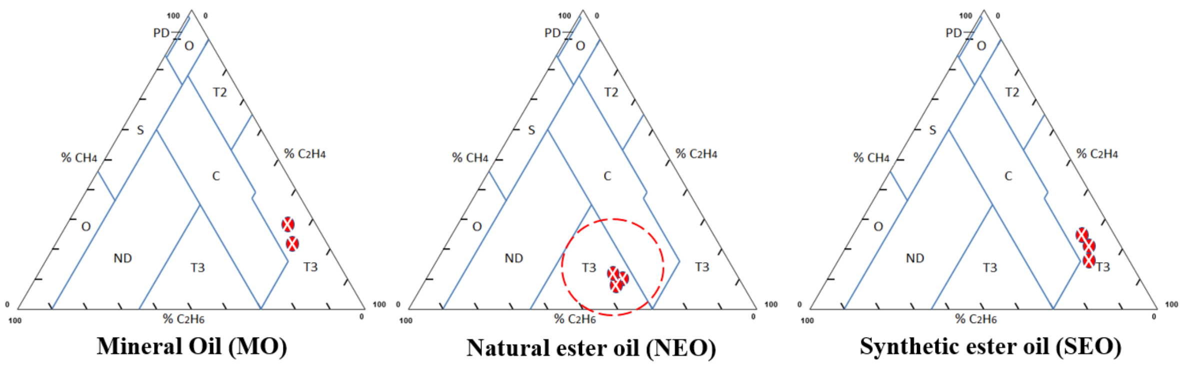

Fig. 7. Thermal fault positions in Duval Triangle 5 for MO, NEO, and SEO.

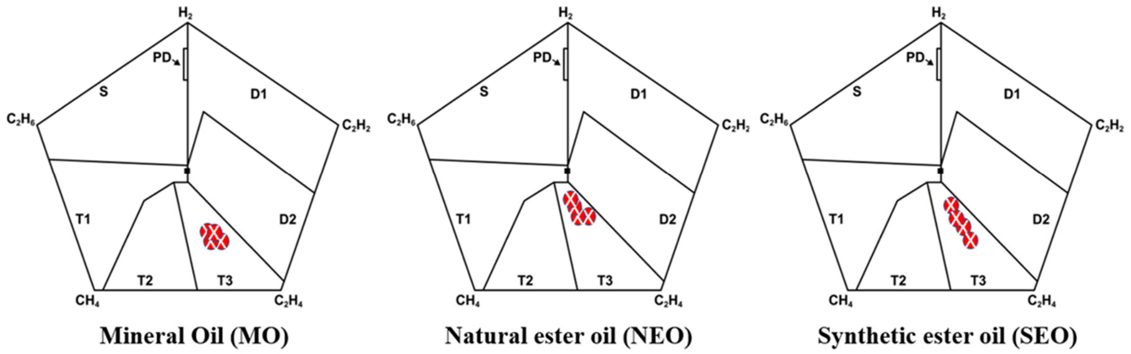

Fig. 8. Thermal fault positions in Duval Pentagon 1 for MO, NEO, and SEO.

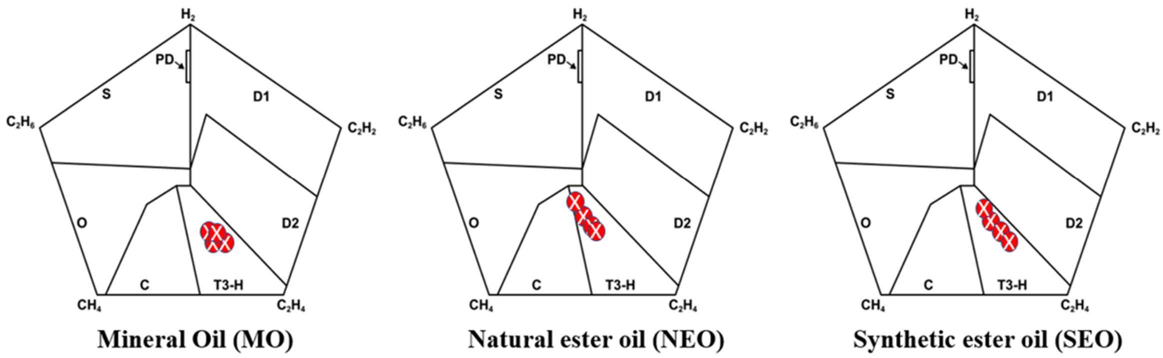

Fig. 9. Thermal fault positions in Duval Pentagon 2 for MO, NEO, and SEO.

E. Duval Pentagon Method

The Duval pentagon 1 uses all five hydrocarbon gases (H_2, C_2H_6, CH_4, C_2H_4, and C_2H_2) [21]. The order of gases at the five summits of pentagons 1 and 2 corresponds to the increasing energy or temperature of the faults producing these gases (from H_2 to C_2H_2). The six basic fault types (PD, D1, D2, T1, T2, and T3) can be detected with Duval pentagon 1, as in the case of Duval triangle 1. If thermal faults (T1, T2, and T3) are identified with Duval pentagon 1, more information can be obtained on them with Duval pentagon 2 [22]. As portrayed in Figures 8 and 9, all three oil types demonstrated a high-temperature thermal fault T3 when subjected to high-intensity thermal stress. Duval pentagon is a highly effective interpretation method in case of thermal fault T3. All 6 cycled DGA measurement points fell in same T3 region in Duval pentagon 1. Duval pentagon 5 also confirmed the thermal fault of T3.

F. Key Findings

The key findings of this study on the analysis of dissolved gases generated during high-temperature faults in ester-based liquid insulation are:

- NEO and SEO generated C_2H_4 and H_2 as key gases under high-temperature fault conditions, similar to those of MO. This suggests that these gases can be used as reliable indicators in comparative studies of different insulation oils.
- Initially, NEO produced a higher amount of C_2H_4, but its rate of increase slowed down with continuous energy application. In contrast, the rate of increase in C_2H_4 was higher in SEO.
- Methane, acetylene, and propylene were generated similarly in all three types of oils, but ethylene was produced more in NEO under similar hotspot conditions.
- Propane was produced more in NEO and SEO than in MO, indicating its significance as a key gas in high-energy thermal faults for ester-based oils.
- The increase in gas percentages with prolonged hotspot duration emphasizes the importance of time-based studies to gauge the cumulative effects of thermal stress. The limitations of the Doernenburg, Rogers, and IEC ratio methods in confirming thermal faults (T3) in NEO and SEO, as opposed to their effectiveness in MO, stress the need to refine these methods or develop new ones tailored to ester-based oils.
- The validation of thermal fault T3 across all oil types by the Duval triangle 1, Duval triangle 5, Duval pentagon 1, and Duval pentagon 2 methods indicates their robustness and applicability in diverse experimental contexts.

Future research can benefit from these insights by incorporating the aforementioned reliable diagnostic methods into experimental designs and exploring their potential modifications to enhance accuracy for different types of liquid insulation. This comprehensive approach enhances the reliability and applicability of the findings across various insulation oil studies.

IV. CONCLUSIONS

The employment of Natural Ester Oil (NEO) and Synthetic Ester Oil (SEO) in transformers, in addition to Mineral Oil (MO), is a recent breakthrough in the transformer industry. The compatibility and functionality of these esters have been explored. However, there is little information on fault diagnosis for NEO and SEO by Dissolved Gas Analysis (DGA) and employing all diagnostic techniques that have been conducted on MO.

This study presents a comparative analysis of the dissolved gases generated during high-temperature thermal faults (T3) simulated under laboratory conditions using all three types of oils. High-temperature thermal faults (T3) have high intensity and can lead to the catastrophic failure of transformers. The interpretation of DGA has been examined for fault diagnosis using five methods: Doernenburg ratio, Roger ratio, IEC 60599 basic gas ratio, Duval triangles, and Duval pentagons. Each interpretation method has its advantages and limitations, necessitating the use of multiple methods for fault diagnosis. Based on the results of this study, it is proposed that Duval triangles and pentagons be used for interpreting high-temperature thermal faults (T3) in ester-based insulating oils. Further research on the rate of increase of ratios under different thermal fault conditions is proposed to explore their utility.

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