Dissolved Gas Analysis (DGA) of canola-based ester fluid

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Declaration

I declare that this dissertation is my own, unaided work, other than where specifically acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Abstract

This dissertation presents the investigation of the Dissolved Gas Analysis (DGA) of canola-based ester fluid when subjected to a high energy discharge fault. Recently, ester fluids have been introduced to transformers to replace the widely used mineral oil due to better fire safety and biodegradability characteristics of the organic insulating fluids. The introduction of ester fluids in power transformers raises the need for investigating the DGA of ester fluid given the difference in the chemical structure of ester fluid with mineral oil.

The high energy discharge in the canola-based ester fluid was generated by the application of an A.C voltage sufficient to cause continuous breakdown across an electrode gap for 15 seconds. The resulting dissolved gases reveal that the even though, the type of gases dissolved in the canola-based ester fluid are similar to those in mineral oil, the quantities of the dissolved hydrocarbon gases are lower in the ester fluid. Also, the ester fluid generates higher amounts of carbon oxides, and additional ethane. An evaluation of the traditional DGA interpretation methods revealed that the IEC 60599 ratios, Roger's ratios and the newly developed Duval's triangle three (BIOTEMP and FR3) can in average correctly identify the high energy discharge in the canola-based ester fluid. However, the IEEE key gas method requires modification to accommodate the production carbon oxides produced in the canola-based ester fluid.

For future work, it is recommended that higher voltages in the range of in-service transformers are used for the high energy discharge. This is to ensure that all effect that could results in actual service transformers are fully studied. Also the work is recommended to be extended to other various types of ester fluids.

Dedication

This dissertation is dedicated to my daughter; Sinethemba Ndaloenhle Mashaba.

"I hope you find more reason to believe than to fear."

– Unknown

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Lastly, to my life partner, Musa Mashaba, thank you for your unending support and for always believing in me. And to my family I hope this dissertation will be an inspiration for the next generation.

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Glossary of Terms and Abbreviations

Table 1: Chemical names

Abbreviation/Term	**Description**
H_2	Hydrogen
CO	Carbon monoxide
CO_2	Carbon dioxide
CH_4	Methane
C_2H_6	Ethane
C_2H_4	Ethylene
C_2H_2	Acetylene
N_2	Nitrogen
O_2	Oxygen
DGA	Dissolved Gases Analysis
AC	Alternating Current
CIGRE	Counseil International des Grands Reseax Electriques
IEEE	Institute of Electrical and Electronic Engineers
IEC	International Electrotechnical Commission
SAUPEC	Southern African Universities Power engineering Conference
PRASA	Annual Symposium of the Pattern Recognition Association of South Africa
RobMech	Robotics and Mechatronics Conference of South Africa

List of publications

[1] H. F. Mnisi, C. Nyamupangedengu. "Investigation of the application of Dissolved Gas Analysis (DGA) in canola-based natural ester oil under arcing fault", *9th CIGRE Southern Africa Regional Conference*, October 2019, Johannesburg, South Africa- **Best Paper Award**

[2] H.Mnisi, C. Nyamupangedengu. "Dissolved Gases Analysis of canola-based ester fluid under creepage discharges", 2020 SAUPEC/RobMech/PRASA Conference, January 2020, Cape Town, South Africa.

Chapter 1 – Introduction

Mineral insulation oil is widely used in power transformers to insulate the energised parts of the transformer and to cool the transformer by dissipating heat [1]. However, mineral oil has limitations since it is highly flammable and non-biodegradable [2]. Ester fluid has been proven to be the potential alternative power transformer insulating liquid due to its low flammability and biodegradability [3]. Ester fluid has been successfully applied in distribution transformers and it is gaining popularity in higher voltage power transformers. In South Africa, the national power utility; Eskom; signed a memorandum of understanding for replacing the conventional mineral oil with ester fluid in all distribution-level transformers [4].

In power transformers, condition monitoring of the internal insulation system is crucial for the prevention of transformer failure. Dissolved Gas Analysis (DGA) is one of the most reliable condition monitoring technique that is used to detect and identify incipient faults developing inside mineral oil-filled transformers [5-6]. DGA detects incipient faults based on the analysis of gases that are dissolved in the insulation liquid. The gases form and dissolve in the insulation liquid as a result of internal electrical or thermal faults that occur during the operation of the transformer. These faults degrade the insulation (liquid and solid insulation) resulting in the formation of various low molecular gases that dissolve in the insulation liquid. The analysis of these dissolved gases identifies the type of internal faults that are developing inside the transformer. The ability to detect and identify incipient faults is important for preventative maintenance that enables proactive actions to be taken timeously to avert transformer damage and failure, and henceforth extend transformer life. With the evolution of the transformer insulation technology from mineral oil to the organic ester fluid, a challenge arises regarding how to modify the corresponding diagnostic techniques.

1.1 Problem description

The introduction of ester fluids in power transformers requires corresponding reliable condition monitoring techniques to detect anomalies at an early stage so as to initiate maintenance timeously in order to prevent transformer failure and damage. DGA has been developed for and successfully used in mineral oil-filled transformers for condition monitoring. However, DGA is a function of the chemistry of the insulation liquid. Ester fluid has a different chemical structure to mineral oil, hence extensive work has been done to investigate the DGA of ester fluids.

The majority of published literature on the DGA of ester fluids mainly focuses on partial discharges, thermal faults and low energy discharges; the knowledge on DGA under high energy discharges is still minimal and inconclusive [7-8].

1.2 The research objective and research questions

The objective of this research is therefore to investigate the dissolved gases in a canola-based natural ester fluid under high energy discharge fault. The objective of this research is achieved by answering the research questions:

i. What are the difference(s) in the gas generation composition between canola-based ester fluid and mineral oil under high energy discharge?
ii. What are the implications on the applicability of existing DGA diagnosis methods on the canola-based ester fluid?

1.3 Dissertation structure

The structure of this dissertation is as follows:

Chapter 2: The background of transformer insulation liquid is presented in this chapter. The limitations of mineral oil that has led to the motivation of using ester fluid as an alternative are discussed in detail.

Chapter 3: The theoretical background of DGA diagnostic technique as used in mineral oil-filled transformers is presented in this chapter; this includes the mechanism of gas formation, the types of faults identifiable by DGA and the identification of the internal faults through DGA diagnosis methods.

Chapter 4: This chapter reviews the existing literature of DGA of ester fluids and highlights the knowledge gap that is engaged by this dissertation.

Chapter 5: This chapter presents benchmark experimental tests conducted on the canola-based ester fluid as a precursor to the DGA of high energy discharges.

Chapter 6: The literature of the DGA of high energy discharges is presented in this chapter. The literature review leads to the knowledge gap in the DGA of ester fluids.

Chapter 7: This chapter discusses the experimental set up that is used to generate the high energy discharge.

Chapter 8: The experimental results and the analysis of the results is presented in this chapter.

Chapter 9: In this chapter, the dissertation is concluded and recommendations for future work are presented.

Chapter 2 – Background

This chapter discusses the theory on the function of insulation liquids in power transformers. An emphasis is placed on the motivation that has led to the introduction of ester fluids as an alternative to mineral oil in power transformers.

2.1 Transformer insulation liquid

Power transformers are used to transform voltage and current for the transmission of electricity over long distances and the distribution of electricity to customers [1]. The basic function of transformers is achieved by the use of primary and secondary windings. The primary and secondary windings are required to be insulated from each other, from the transformer core and from the transformer tank. The insulation system of a transformer is then used for this main purpose [1]. Pressboard insulation is commonly used between transformer windings and between windings and core. The pressboard insulation inherently contains small air voids due to the manufacturing process [1]. The presence of the small air voids subsequently decreases the insulation strength of the pressboard [1]. The solution to this is the impregnation of the pressboard insulation with liquid insulation. The impregnation of pressboard with insulation liquid results in increased pressboard dielectric strength which subsequently increases the reliability of the insulation system.

The second function of insulation liquid is to cool the transformer through heat dissipation. When power transformers are in operation, heat is produced in the transformer. The heat is produced from the windings as a result of copper losses and losses in the core [1]. The heat is dissipated from the transformer through the process of convection and conduction [1].

The third function of transformer insulation liquid is providing diagnosis for the health of the transformer [1]. Stresses that are imposed on a transformer while in operation result in the production of insulation material degradation by-products that can be detected via the assessment of the insulation liquid. There are various techniques that are used for the diagnosis of the transformer condition through the insulation liquid. These techniques include insulation liquid colour, dielectric breakdown strength, power factor, interfacial tension, neutralization number, moisture content, DGA and etc. [9].The use of insulation liquid for DGA diagnostic purposes is the subject of this dissertation and is further discussed in the next chapters.

2.2 Mineral insulation oil

Mineral oil is the commonly used insulating liquid in power transformers due to its good dielectric properties, desirable cooling properties, low viscosity and relative low cost [1-2]. The oil is derived from the distillation and refinement of crude petroleum oil [1-2]. Mineral oil is a combination of different hydrocarbon molecules which are; paraffinic, naphthenic and aromatic. These hydrocarbons are composed of CH, CH_2 and CH_3 groups linked by carbon-carbon bonds as shown in Figure 1 [2]. Naphthenic and paraffinic mineral oil are the two types of mineral oil that are used for power transformer insulation purpose.

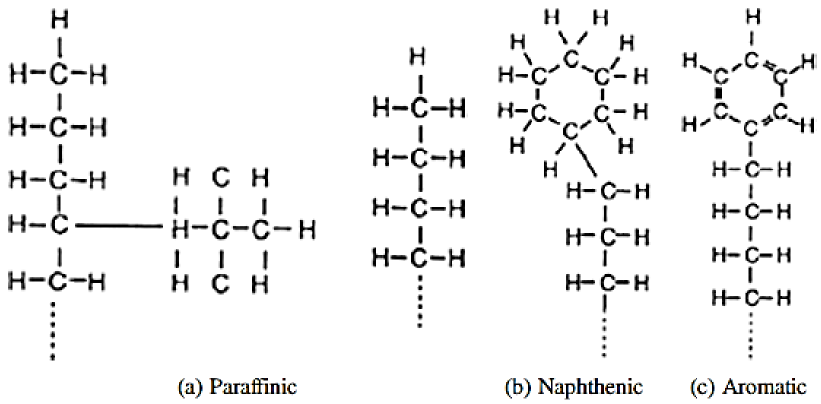

Figure 1: Chemical structure of mineral oil compounds as adapted from [2]

Despite the good dielectric properties and good heat dissipation of mineral oil, the oil is also characterized by undesirable properties which are; high flammability, poor biodegradability, poor moisture tolerance and it is non-renewable [2, 10].

These limitations of mineral oil and the heightened environmental concerns have led to the research and development of alternative insulation liquids and ester fluid has been proven to be suitable for use in transformers [2, 10].

2.3 Ester insulation fluid

Ester insulation fluids have been considered as alternative insulating fluids to mineral oil. This is because ester fluids are less flammable compared to mineral oil, are fully biodegradable and renewable [10-12].

Two types of ester insulation fluids exist; natural ester and synthetic ester. Natural ester fluids are derived from vegetable seeds such as canola, soya, flax, olive, poppy, and sunflower seeds [10-12]. Natural ester fluids are chemically composed of three saturated and unsaturated fatty acids groups connected to glycerol/glycerine molecule to form a triglyceride as shown in Figure 2 [13]. Synthetic ester fluid is composed of synthetic or natural carboxylic saturated acid connected to polyol molecule (a molecule with more than one alcohol functional group) as shown in Figure 3 [13].

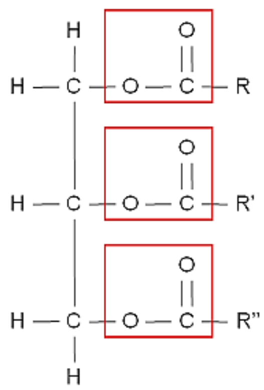

Figure 2: Chemical structure of natural ester oil as adapted from [13]

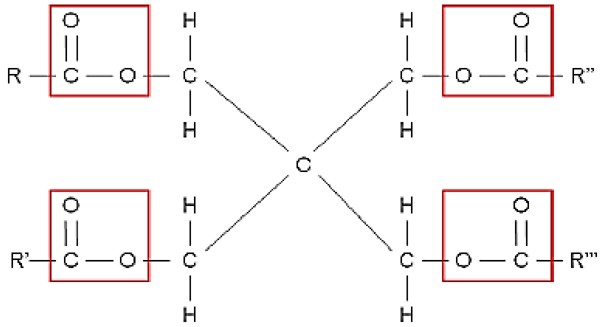

Figure 3: Chemical structure of synthetic ester oil as adapted from [13]

The chemical structures of ester fluids are completely different from that of mineral oil. The difference in the chemical structures of ester fluids to mineral oil gives ester fluid additional desired properties including biodegradability, low flammability and moisture solubility. Other comparative characteristics of ester fluids to mineral oil are discussed in the following sections.

2.4 Comparison of mineral oil and ester fluids

A comparison of the properties of mineral oil and ester fluids that have deemed ester fluids a potential alternative insulation liquids are as follows:

2.4.1 Biodegradability

Power transformers are filled with large quantities of insulating liquid. In the case of mineral oil leakage or transformer explosion, the mineral oil is spilled to the immediate environment. The poor biodegradability of mineral oil is harmful to the environment since a spillage/leakage can lead to contamination of water and the soil [14]. Contamination of ground water sources by insulation oil has negative effects on water inhabitants since the oil can result in lack of oxygen [14]. Consequently, large financial penalties are normally imposed on utilities by environmental enforcement agencies as a result of mineral oil spillage/leakage.

Ester fluid is fully biodegradable; within 28 days of oil leakage/spillage, the fluid completely biodegrades. A comparison of the level of biodegradability between various commercial ester fluids with mineral oil within 28 days is given in Table 1

[10]. The biodegradability property of ester fluids implies that insulation liquid containment measures and bund walls which are normally fitted in mineral oil-filled transformers can be simplified for ester fluid-filled transformers, leading to a reduction in transformer installation costs.

Table 1: A comparison of biodegradability of mineral oil versus ester fluid

Type of insulation fluid	**Biodegradability**
(Nynas) 10GBN mineral oil	< 10%
Midel 7131 synthetic ester fluid	Readily biodegradable
FR3 natural ester fluid	Readily biodegradable
BIOTEMP	Readily biodegradable

2.4.2 Insulation liquid flammability

The failure of mineral oil-filled power transformer normally results in catastrophic fires. The fires pose a risk to equipment and to human life. The downtime cost related to transformer fires and transformer replacement is very costly [15]. Transformer fires are difficult to manage hence fire safety measures are normally required for mineral oil-filled transformers. Typical fire measures include firewalls, deluge systems and fluid containment, and these measures contribute a significant portion to the power transformer installation cost [15].

Ester fluid has a high flash and fire point compared to mineral oil as presented in Table 2 [10]. The flash point is defined as the lowest temperature at which the liquid can form a vapour near its surface that will flash or briefly ignite when exposed to an open flame [16]. The fire point is defined as the temperature at which the insulation liquid will continue to burn after ignition for at least five seconds [16]. This implies that ester fluid requires relatively higher temperatures to catch a fire as compared to mineral oil. Hence ester fluid is less flammable compared to mineral oil. The low flammability of ester fluid is highly desirable since there is no fire risk posed by this fluid and there is less installation cost since fire barriers equipment can be simplified or omitted [10]. Furthermore, the high fire point of ester fluids aids in improving the thermal capability of insulation paper in power transformers [17].

Table 2: A comparison of fire and flash point of mineral oil and ester fluid [10]

Type of insulation liquid	**Fire point [°C]**	**Flash point [°C]**
Mineral	170-180	160-170
Synthetic ester	>250	>300
Natural ester	>350	>300

2.4.3 Moisture tolerance

The presence of moisture is unavoidable inside a power transformer, although measures are taken to prevent atmospheric moisture ingress. The sources of moisture include; humid air from external environmental which enters through free breathing, remaining moisture from manufacturing process, leaks, insulation liquid topping, moisture from new cellulose, moisture ingress via the gasket or a by-product of cellulose degradation [1]. Moisture is unwanted inside a transformer since it is known to reduce the dielectric strength of the insulation liquid as well as the mechanical strength of the cellulose insulation by accelerating the ageing rate of the cellulose insulation [1]. The reduction of the dielectric strength of the cellulose insulation subsequently results in the reduction of transformer life.

Ester fluids are hygroscopic in nature; have the tendency to absorb moisture [18]. The hygroscopic nature of ester fluids is attributed to the COOR linkage in the molecular structure which has a higher ability to participate in hydrogen bonding, hence absorbing moisture. The high ability of ester fluids to absorb moisture implies that moisture has a lesser impact on ester fluid-filled transformers compared to mineral oil-filled transformers. This results in cellulose insulation being kept in a drier state and the rate of cellulose degradation consequently is slower in ester fluid-filled transformer than in mineral oil-filled transformer. Consequently the life span of cellulose insulation is increased. A comparison of water saturation at room temperature between ester fluid and mineral oil is given in Table 3 [10, 18].

Table 3: Water saturation of mineral oil versus ester fluid [10]

Type of insulation liquid	Water saturation [ppm]
Mineral oil	55
Synthetic ester fluid	2600
Natural ester fluid	1100

2.5 Disadvantages of ester insulation fluids

Although ester fluids have the desirable properties as discussed in Section 2.4. However, the ester fluid also has shortcomings.

2.5.1. Viscosity

As aforementioned, the main function of transformer insulation liquid is providing cooling. The ability of an insulation fluid to provide cooling is dependent on its viscosity [10]. Ester insulation fluids are more viscous compared to mineral oil, this implies that the flow of ester insulation fluid in the winding ducts of a transformer is slower compared to mineral oil [10]. Consequently, the operating temperature of ester filled transformers is higher than mineral oil filled transformers. This shortcoming of ester fluids requires a modification in the design of the winding ducts of ester-filled transformers.

2.5.2. Oxidation stability

Natural ester fluids are more susceptible to oxidation compared to mineral oil [10, 15]. This is due to the presence of the carbon-carbon double bond in the chemical structure of ester fluids [15]. The oxidation of natural ester fluids results in the formation of acids, alcohols and complex molecules that can further increase the viscosity of the fluid. The oxidation of natural ester fluids can be limited by designing natural ester fluid-filled transformers with sealed tank [10, 15].

2.6 Chapter summary

Although mineral oil is the widely used transformer insulation liquid, the heightened environmental and safety concerns of this fluid have resulted in the development of ester insulation fluid. Ester fluid is considered an alternative transformer insulation liquid since it is less flammable and fully biodegradable. But, the dielectric characteristics which include the degradation products of the ester fluid are not yet fully understood. The following chapters detail the investigation of one of these degradation products; dissolved gases of the ester fluid when the fluid is subjected to typical transformer faults.

Chapter 3 – DGA diagnostic technique

This chapter details the principle of DGA as a diagnostic technique used in mineral oil-filled transformers. An emphasis is placed on the gas formation mechanism which explains how gases are formed in mineral oil through the decomposition of the oil. An understanding of the gas formation mechanism in mineral oil aids in the contextualisation of the importance of investigating the DGA of ester fluid.

3.1 An overview of DGA diagnostic technique

DGA is a condition monitoring tool that is used to detect incipient faults that are developing inside a power transformer. DGA detects and identifies incipient faults before they develop into major faults [5-6]. The detection of incipient faults aids in the prevention of unplanned outages and equipment damage & failure; maximizing transformer lifetime and improving the reliability of the power system [5-6].

DGA is based on quantifying gases dissolved in insulation liquids and identifying the type of incipient fault through diagnostic methods. Gases are mainly dissolved in insulating liquid when the transformer insulation liquid is exposed to thermal or electrical faults. The electrical and thermal stress produce energy that breaks down the molecular/chemical bonds of the insulation liquid to produce hydrocarbons gases which in turn dissolve in the insulation liquid [5-6, 19-20].

Also, gases are dissolved in insulation liquid as a result of the degradation of the polymer materials of cellulose insulation [5-6, 19-20]. The degradation of cellulose insulation in mineral-oil filled transformers is known to produce carbon monoxide and carbon dioxide as a result of the breaking of C-O molecules that make up the insulation material. It would be interesting to evaluate if the presence of CO and CO_2 is still indicative of cellulose degradation in ester fluids as well.

The premise of DGA for in-service transformers is therefore based on sampling the transformer liquid using specialised tools, extracting the gases from the liquid through gas chromatography and identifying the type of developing fault through diagnostic methods.

DGA is one of the most reliable insulation diagnostic technique that has a 70% success rate in the diagnosis of the common failures in mineral oil-filled transformers [2]. The type of transformer faults detected through DGA are discussed in the next section.

3.2 Faults detectable using DGA

The objective of DGA is to detect and identify incipient faults before they develop into major faults. The identification of these faults is not an exact science, it is based on the correlation judgement of dissolved gases to a fault type. The knowledge on the correlation of dissolved gases to a fault type is a result of historical data collected over many years of mineral oil-filled transformers that have failed in service [19-20]. The data was used to correlate the gases dissolved in the oil with the type of a fault that had occurred on the transformer based on visual inspection and various transformer tests. Since the mineral oil-based DGA knowledge is largely based on historical data and ester fluids are relatively new in the market. Then, the DGA of ester fluids (which is still developing) has been derived from the knowledge of mineral oil-filled transformers.

There are six main types of faults detectable by DGA as standardised in IEC 60599 [20]. They are; partial discharges of the cold plasma type (PD), low energy discharges (D1), high energy discharges (D2), Thermal T1 (temperature < 300°C), Thermal T2 (300 °C<temperature < 700 °C) and Thermal T3 (temperature > 700 °C) [9]. These six types of faults correspond to various typical transformer faults as given in Table 4 [20].

Table 4 [20]: DGA fault characteristics and typical transformer faults

Type of fault	**Typical transformer fault**
Partial discharge (of the corona type)	Discharges in gas-filled cavities resulting from incomplete impregnation, high humidity in paper, oil super saturation or cavitation and leading to X-wax formation
Low energy discharges	Sparking or arcing between bad connections of different floating potential, from shielding rings, toroids, adjacent disks or conductis of windings, broken brazing or closed loops in the core. Discharges between clamping parts, bushing and tank, high voltage and ground within windings. Tracking in wooden blocks, glue of insulating beams.
High energy discharges	Flashover, tracking, arcing with high local energy. Short circuit between high voltage and ground, connectors, windings, bushing and tank, copper bus tank, windings and core. Closed loops between adjacent conductors.
T1	Transformer overloading, restricted oil flow in windings, stray flux in clamping beams.
T2	Defective contacts between bolted connections, gliding contacts, connections from cable and draw-rod of bushing. Circulating currents. Abraded insulation between adjacent parallel conductors in windings.
T3	Large circulating currents in tank and core. Minor circulating currents in tank walls. Shorting links in core steel laminations.

3.3 Gas formation mechanism in mineral insulation oil

When mineral oil-filled transformers are in service, gases are formed in the insulation oil. The formation of these gases in mineral oil is mainly attributed to thermal and electrical faults. The thermal energy from the faults decomposes the oil by breaking the complex hydrocarbon (C-H and C-C) molecules which make up the oil. The breaking of the hydrocarbon molecules results in the formation of free radicals such as CH_3*, CH_2*, CH*, C* and H* [19-20]. These radicals subsequently combine with each other via complex reactions to form gas molecules which include hydrogen (H-H), methane (CH_3-H), ethane (CH_3-CH_3), further decomposition produces ethylene (CH_2=CH_2) and acetylene (CH ≡ CH). These gas molecules are dissolved in the insulation oil and used for DGA analysis.

The formation of the different gases is commonly explained according to the Halstead model [5, 19]. The Halstead model is a thermodynamic model that is based on correlating the relative gas concentration to the temperature of the fault. The Halstead model assumes that the hydrocarbons in the oil are decomposed into the same product and that each product is in equilibrium with all the others.

The typical evolution of gas generation as a function of fault temperature in mineral oil is given in Figure 4 [5]. Figure 4 illustrates that low temperature faults such as partial discharges results in the breaking of the weakest C-H bonds, thereby producing Hydrogen. An increase in temperature (more energy) favours the breaking of the C-C bonds which results in the production of methane and small traces of Hydrogen. As the temperature increases further, ethane is formed and the magnitude of methane reduces. Further increases in temperature result in the breaking of double carbon (C=C) bonds resulting in the formation of ethylene. At even higher temperatures, acetylene is formed. The formation of acetylene requires temperatures of at least 800 °C – 1200 °C as illustrated in Figure 4.

Furthermore, the dissociation enthalpies at standard temperature and pressure required for breaking the various DGA gases is summarised in Table 5 [21].

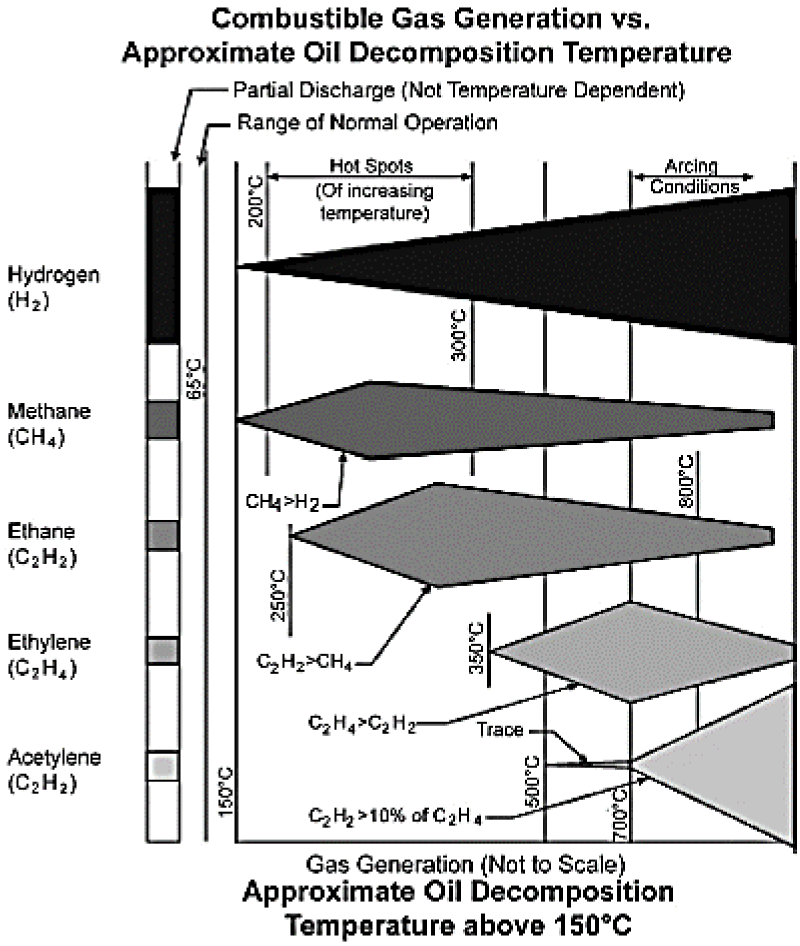

Figure 4: Gas generations as a function of temperature, as adapted from [5]

Table 5: Dissociation enthalpies of chemical bonds [21]

Type of bond	Dissociation enthalpy [kJ/mol] @standard temperature of 25
C-C (CH3- CH3)	356
C-H	410
C=C (H2C=CH2)	632
C≡C (HC≡CH)	837

3.4 Detection of faults using DGA

The purpose of DGA is to detect developing incipient faults and identify the type of developing fault. The detection of developing faults is normally observed by gas values which exceed the standardised typical values [19]. Transformers generates gases under normal conditions. The gas values which are indicative of normal transformer gassing are known as typical concentration values [20]. When dissolved gases values of a transformer exceed the typical values, diagnosis methods are used to identify the type of developing fault and preventative maintenance actions are taken to prevent transformer damage.

The typical gas concentration values were developed based on more than 20000 power transformers worldwide. The values are summarised in Table 6 [20].

Table 6: Typical gas concentration values for in-service transformers

Gas	**Typical gas concentration**
C_2H_2	0
H_2	50-150
CH_4	30-130
C_2H_4	60-280
C_2H_6	20-90
CO	400-600
CO_2	3800-14000

3.5 Identification of faults using DGA Diagnosis methods

As previously stated, there are six basic categories of faults that are detectable and identified by DGA. In general, multiple diagnosis methods are normally used in conjunction with each other to triangulate and ensure that a more accurate identification of a fault is achieved.

There are various diagnosis methods that have been developed over years. The typical DGA interpretation methods are; IEEE Key Gas method, IEC 60599 ratios, Rogers and Doernenburg ratios, Duval's triangle, Duval's Pentagon, Artificial Neural Networks, Fuzzy Logic, Support Vector Machine, Expert systems, Hybrid Systems and etc. [22]. The generally accepted and widely used interpretation schemes in utilities are; Duval's triangle, Rogers ratios, IEC 60599 ratios and IEEE key gas [23]. The principles of each of these interpretation methods are presented in the next sub-sections.

3.5.1 IEEE C57.104 (2008) Key Gas interpretation method

This diagnosis method uses the concept of key dissolved gas to identify the incipient fault. There are four general types of faults that are identified using this diagnosis method as summarized in Table 7 [19]. It is notable that the high energy discharge is referred to as high intensity arcing in this diagnosis method.

The key gas method is generally used by most utilities, however, it has been found to produce 50% incorrect fault diagnosis [23].

Table 7: IEEE Key gas interpretation method

Type of fault	Key gas	Secondary gas (es)
Partial discharges and Low energy discharges including partial discharge	Hydrogen (85%)	Methane (13%) and small traces of ethane (1%) and ethylene (1%)
Thermal fault in oil	Ethylene (63%)	Ethane (19%), Methane (16%) and small traces of hydrogen (2%)
Thermal fault in cellulose	Carbon monoxide (92%)	Carbon dioxide and small traces of methane and ethylene
High intensity arcing	Acetylene (30%)	Hydrogen (60%) and minor quantities of methane (5%) and ethylene (3%)

3.5.2 The Rogers Ratios DGA interpretation method

The Rogers Ratios diagnosis method is based on the ratios of five fault gases for the identification of the incipient fault [19]. The limiting values of the ratios are summarised in Table 8.

The Rogers ratio method fails to correctly identify 15-20% of faults [23]. The misclassification occurs when the proportion of dissolved gases falls due to results outside the ratio boundaries [23].

Table 8: Rogers Ratios DGA interpretation method

Fault type	**C_2H_2/C_2H_4**	**CH_4/H_2**	**C_2H_4/C_2H_6**
Normal deterioration	< 0.1	0.1 - 1	< 1
Low energy arcing	< 0.1	< 0.1	< 1
High energy discharge	0.1 – 3	0.1 - 1	> 3
Low temperature thermal fault	< 0.1	0.1 - 1	1 - 3
Thermal fault < 700 °C	< 0.1	> 1	1 - 3
Thermal fault > 700 °C	< 0.1	> 1	> 3

3.5.3 The IEC 60599 Ratios DGA interpretation method

The IEC 60599 ratios method diagnose incipient faults using three gas ratios from the quantity of five dissolved gases. The three ratios are C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6. This diagnosis method can identify six types of incipient faults based on the values of the gas ratios as summarized in Table 9 [20]. Similar to the Rogers ratios method, the IEC60599 ratios method also has a 15-20% accuracy [23].

Table 9: IEC 60599 faults classification

Fault code	**Fault type**	**C_2H_2/C_2H_4**	**CH_4/H_2**	**C_2H_4/C_2H_6**
PD	Partial discharges (of the cold plasma type)	Not significant	< 0.1	< 0.2
D1	Discharge of low energy	> 1	0.1 - 0.5	> 1
D2	Discharge of high energy	0.6 - 2.5	0.1 - 1	> 2
T1	Thermal fault (T < 300 °C)	Not significant	> 1	< 1
T2	Thermal fault (300 -700 °C)	< 0.1	> 1	1 - 4
T3	Thermal fault (T > 700 °C)	< 0.2	> 1	> 4

3.5.4 Duval's Triangle DGA interpretation method

The Duval's triangle interpretation method uses a triangular graphical method to classify a transformer fault. The three axes of the triangle classic triangle 1 are a representation of relative percentage of three gases; C_2H_4, CH_4, and C_2H_2, and the interior of the triangle is subdivided into fault zones as shown by Figure 5 [24]. The fault zones (PD, D1, D2, T1, T2, and T3) refer to the fault types as described in the IEC 60599 standard. The criteria used for the classification of faults are given in Table 10 [24].

The Duval's triangle diagnosis method has the highest level of accuracy since it is a closed system and since it was developed using a large historical database [23]. Since the Duval's triangle uses the IEC 60599 faults classifications, it inherently identified a high energy discharge fault.

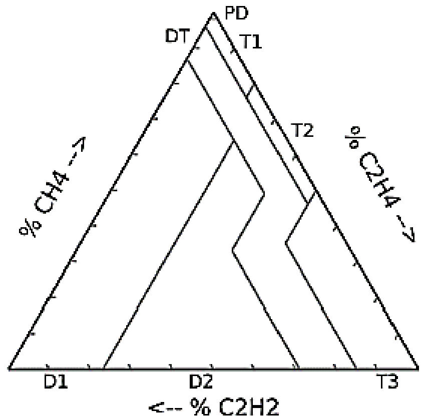

Figure 5: Classic Duval's triangle as adapted from [24]

Table 10: Duval's triangle interpretation method fault classification

Duval triangle fault code	**Fault type**	**% CH_4**	**% C_2H_2**	**% C_2H_4**
PD	Partial discharge	98	0	0
T1	Thermal fault of temperature less than 300 °c	0	< 4	< 20
T2	Thermal fault of temperature range of 300 – 700 °C	0	< 4	20 -50
T3	Thermal fault of temperature range of 300 – 700 °C	0	< 15	> 50
D1	Low energy discharge (sparking)	0	> 13	< 23
D2	High energy discharges (arcing)	0	13-29	23 - 38
		0	> 29	> 23
DT	Mix of thermal and electrical faults	Rest area	0	0

3.6 Chapter summary

This chapter has outlined that DGA techniques of mineral oil could be regarded as a mature technology as much as the mineral oil insulation technology is. In contrast, the DGA of ester fluid is not yet mature since the ester fluid insulation technology is still developing. Therefore, the DGA diagnosis technique of ester fluids has been an ongoing development as outlined in the next chapter.

Chapter 4 – The DGA of ester transformer insulation fluid

The previous chapter has demonstrated that the dissolved gases generated under various faults in mineral oil are a function of the chemical structure of the mineral oil. Thus, the introduction of ester fluid as an alternative requires the investigation of the DGA of this type of insulation liquid. Therefore, this chapter reviews this literature of DGA in ester fluid. The review of the DGA of ester fluid assist in contextualising the knowledge gap in this field and the motivation of this dissertation.

4.1 An overview remark

The existing DGA of mineral oil-filled transformers was developed over time using large data of transformers that had failed from service. However, ester fluid has only been relatively recently introduced to power transformers. It has been reported that natural ester fluid was first commercially applied to a power transformer in 2011 [25]. As a result, extensive data of failed ester fluid-filled transformers does not exist yet. Therefore, the existing knowledge of DGA of ester fluid is mainly based on laboratory experiment based data.

4.2 The IEEE C57.155-2014 guide to DGA in ester fluids

Extensive laboratory-based studies of the DGA of ester fluid which have been done overtime have led to the development of the IEEE C57.155 guide. The IEEE guide for interpretation of gases generated in natural ester and synthetic ester- immersed transformers was published in 2014 [25]. The guide is based on studies of different laboratory-simulated faults subjected to ester fluid while using mineral oil as a benchmark. These studies were performed to observe similarities or differences in the gas formation mechanism, gas generation pattern and the effect of these difference(s) or similarities in the mineral oil-based diagnostic methods. A summary of the key knowledge in the IEEE guide is presented in the next sub-section.

4.2.1 Gas formation mechanism in ester fluids

It has been found that the formation of dissolved gases in ester fluid is a result of the breaking of the carbon-carbon and carbon-hydrogen bonds to form radicals as in mineral oil. However, since the chemical structure of ester fluid contains additionally the ester group and carbon chains of at least sixteen carbons, there is a difference in the production, proportion and solubility of the fault gases.

Also, the decomposition of the cellulose insulation in an ester fluid-filled transformer results in the production of carbon monoxide and carbon dioxide as is the case in mineral oil filled transformer.

4.2.2 Gas generation pattern in ester insulation fluids

Thermal faults (T1, T2 and T3) as defined in IEC60599: The studies referred to in the guideline were performed on the common commercially available types of ester fluids, and these include soybean, high oleic sunflower, rapeseed (canola) and synthetic ester fluid. The significant findings of the gas generation pattern observed under the three standardised thermal faults include the following:

- Ethane gas is produced in linolenic ester fluids in the absence of a fault, hence it is considered a characteristic gas for stray gassing.
- Methane, ethane and ethylene are produced in higher quantities in ester fluid than mineral oil.
- Carbon dioxide and carbon monoxide are produced in ester fluids when the fluid is overheated.

Electrical faults (PD, D1): The observation of dissolved gases from partial discharges and D1 faults are as follows:

- The amount of fault gases in synthetic ester fluids is similar to mineral oil, whereas, the amount produced in natural ester fluids is lower (almost ten times lower) than mineral oil.

- The proportion and ratios of fault gases produced in ester fluids is relatively similar to those in mineral oil.

It is worth noting that the IEEE guide has limited and inexplicit knowledge of the high energy discharge faults in ester insulation fluids.

4.2.3 Effect of ester fluids gaseous by-products on DGA interpretation methods

IEEE Key Gas method: In terms of the key gas interpretation method, for partial discharges, Hydrogen is the key gas in ester fluids and acetylene is the key gas for low energy discharge as is the case in mineral oil.

Since the proportion of dissolved gases under partial discharge and D1 faults is relatively similar to mineral oil, the existing interpretation methods can be used for these types of faults.

The high production of ethane, methane and ethylene in natural ester fluids under thermal faults has led to the development of modified versions of the Duval triangles for the diagnosis of various ester fluid. These triangles are discussed in the next section.

4.3 Modified Duval's triangle for fault identification in ester fluids

There are three Duval's Triangles that have been developed for ester fluids; Duval Triangle 3 BIOTEMP, Duval Triangle 3 FR3 and Duval Triangle 3 Synthetic Midel as shown in Figure 6-8 respectively [26]. The three Duval's triangles for ester fluids have been developed by adjusting the thermal fault zones of the classic Duval's triangle. The modification of only the thermal fault zones was done since it has been found that for electrical faults, the traditional Duval's triangle is applicable in ester fluids [25]. The applicability of this finding for canola-based ester fluid is further engaged in the next chapters.

It is worth noting that BIOTEMP is a high-oleic (high quantities of mono-unsaturated fatty acids) natural ester fluid and FR3 is a soya-based high-linolenic (high quantities of di-unsaturated fatty acid) ester fluid. Even though these fluids are both natural esters, but, different triangles have been developed for the diagnosis of faults. This implies that the diagnosis of faults in ester fluids of different chemical compositions requires different interpretation methods

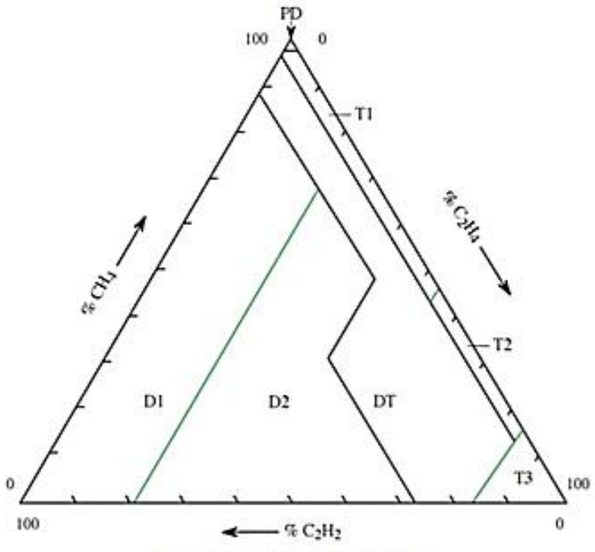

Figure 6: Duval's triangle 3 BIOTEMP as adapted from [26]

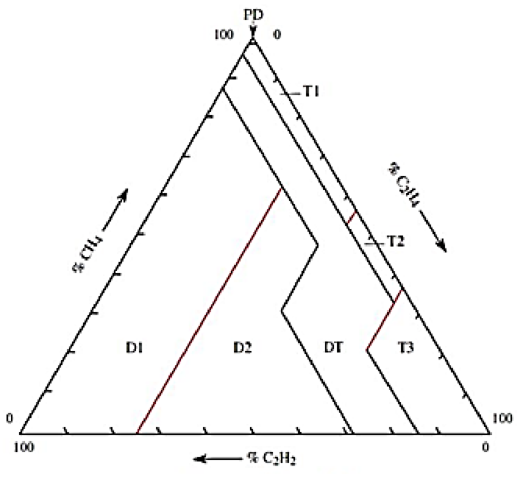

Figure 7: Duval's triangle 3 FR3 as adapted from [26]

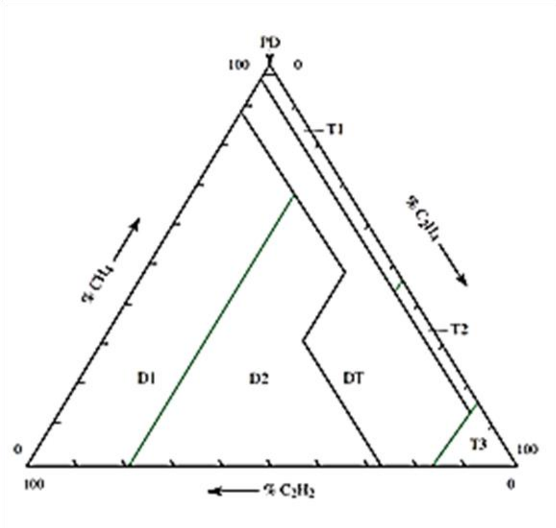

Figure 8: Duval's triangle 3 Midel synthetic as adapted from [26]

4.4 Chapter summary

This chapter has presented the published knowledge on the DGA of ester fluid. The findings illustrate that there are similarities in the DGA of ester fluids with the DGA of mineral oil, particularly under PD and D1 faults. The traditional DGA interpretation methods of mineral oil, are reported to be applicable in the diagnosis of PD and D1 faults in ester fluids. In contrast, modified Duval's triangle have been proposed for the diagnosis of thermal faults.

Chapter 5 – DGA benchmark tests conducted as precursor to DGA of high energy discharge

This chapter presents a summary of the tests performed by the author as benchmark DGA tests prior to exploring the DGA of high energy discharges in canola-based ester fluid in comparison to mineral oil.

Also, the work was done to confirm the existing knowledge of canola-based ester fluid when subjected to D1 and creepage discharges as per the IEEE guideline.

5.1 Investigation of the application of Dissolved Gas Analysis (DGA) in canola-based natural ester oil under low energy arcing fault

A study was done to confirm the DGA of canola-based ester fluid when subjected to a low energy arcing (D1) fault as detailed in Appendix A [27]. The D1 fault was generated by applying A.C. breakdown voltage to a point-sphere electrode configuration using the circuit set-up shown in Figure 9 [27]. The detailed description of the experimental methodology is provided in Appendix A. This work was presented at the 2019 CIGRE Southern African Regional conference.

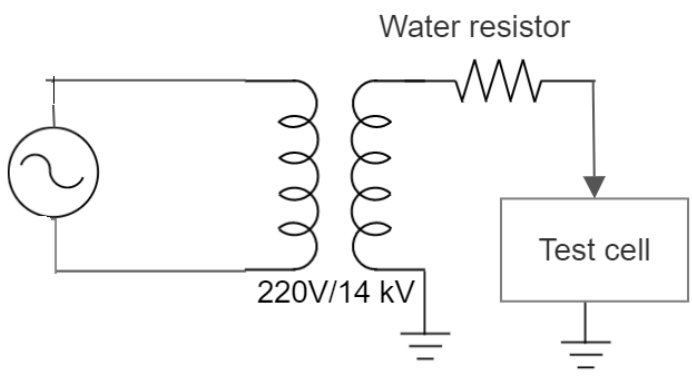

Figure 9: Circuit set up for generating D1 fault

5.1.1. The Dissolved gases results

The resulting gases dissolved in the canola-based ester fluid in comparison to mineral oil are as shown in Figure 10. It is observed in Figure 10 that the composition of dissolved gases is similar and comprises of H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2. However, the proportion of the dissolved gases in the ester fluid is lower than in the mineral oil. These findings are in agreement with the knowledge outlined in the IEEE guideline as discussed in Section 4 [25]. The effect of the dissolved gas composition on the interpretation methods is evaluated in the next sub-section.

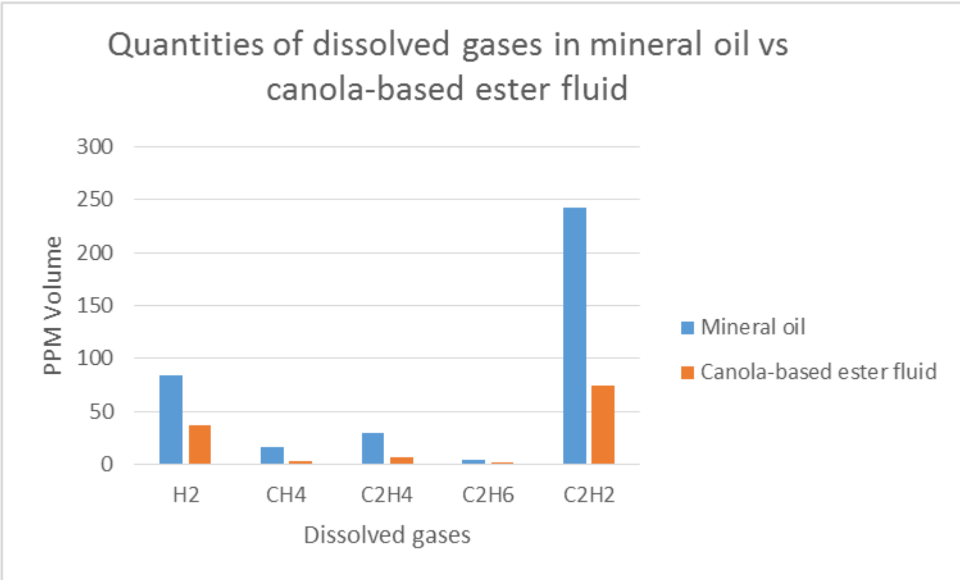

Figure 10: Dissolved gases from low energy arcing fault

5.1.2 Evaluation of interpretation methods applied on obtained results of low energy arc in the canola-based ester fluid

IEEE Key gas method: According to the IEEE key gas method, a low energy arcing fault is characterised by acetylene and hydrogen. This was the case with the resulting dissolved gases found in the canola-ester fluid. Thus, this fault was correctly diagnosed in the canola-ester fluid.

Ratios methods: The results of the IEC 60599 ratios and the Rogers ratios are summarised in Table 11 and Table 12 respectively. It is observed that in Table 11 the Rogers ratios do not correctly identify the low energy arcing fault in both the mineral oil and the ester fluid due to the high value of the C_2H_2/ C_2H_4 ratio. In contrast, the IEC 60599 ratios, can correctly identify the low energy arcing fault in both the mineral oil and the canola-based ester fluid, therefore, confirming the IEEE guideline [25].

Duval's triangles: Duval's Triangle 3 BIOTEMP was used to diagnoses the low energy fault (D1) of the canola-based ester fluid. The BIOTEMP Duval's triangle was chosen instead of the FR3 Duval's triangle since the canola based-ester fluid is mainly oleic as is the case of the BIOTEMP ester fluid. The Duval's triangle correctly diagnosed the fault as a D1 as shown in Figure 11. This finding corresponds with the knowledge in the IEEE guide for ester fluids.

Table 11: Results of Roger's ratios diagnosis

	C_2H_2/C_2H_4	**CH_4/H_2**	**C_2H_4/C_2H_6**	**Diagnosis**
Mineral oil	8	0.2	7.5	No-diagnosis
Canola-based ester fluid	9	0.1	8	No-diagnosis

Table 12: Result of IEC 60599 diagnosis

	C_2H_2/C_2H_4	**CH_4/H_2**	**C_2H_4/C_2H_6**	**Diagnosis**
Mineral oil	8	0.2	7.5	D1
Canola-based ester fluid	9	0.1	8	D1

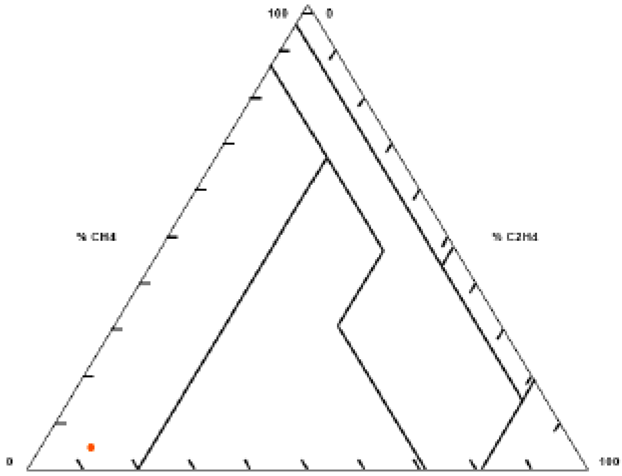

Figure 11: Duval's triangle 3 BIOTEMP diagnosis of canola-based ester fluid

5.2 Dissolved Gases Analysis of canola-based ester oil under creepage discharge

A study was undertaken to investigate the DGA of canola-based ester fluid when subjected to creepage discharges (D1) [28]. The creepage discharges were generated on pressboard insulation that was immersed in canola based-ester fluid while using mineral oil as a benchmark. This work was presented at the 2020 SAUPEC/PRASA/RobMech conference held in Cape Town [28].

The creepage discharges were created using a needle-plane electrode configuration with the pressboard placed between the electrodes. The high voltage was applied through the needle electrode at an acute angle to the pressboard. The application of the high voltage at an acute angle is normally done to ensure that the charges at the tip of the needle electrode are directed to the surface of the pressboard rather than the bulk of the pressboard. The circuit set-up used for this study is as shown in Figure 12.

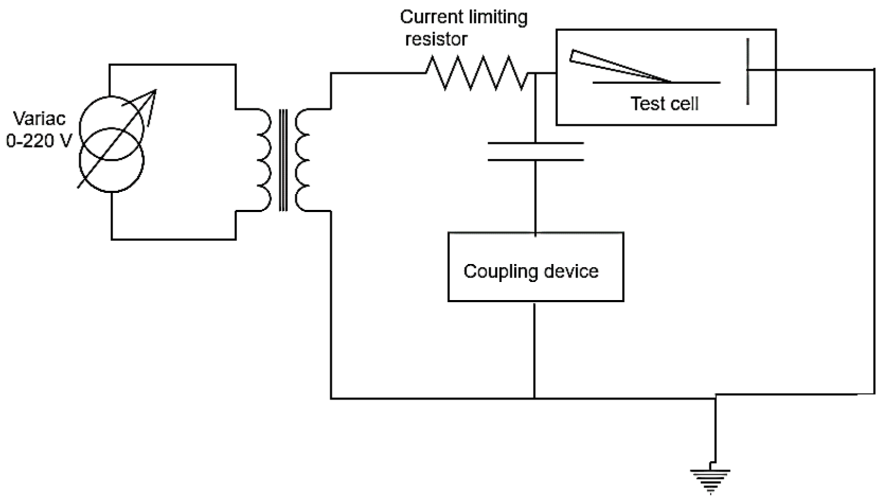

Figure 12: Circuit set-up for generating creepage discharges

5.2.1 Dissolved gases results of creepage discharges

A comparison of the dissolved gases generated from the creepage discharges in the canola-based ester fluid with mineral oil is given in Figure 13. The composition of the dissolved gases in the canola ester fluid and mineral oil is relatively similar. However, the canola based-ester fluid generated higher (four times higher) amounts of hydrogen compared to mineral oil. The high amounts of hydrogen in the ester fluid is attributed to the observed higher creepage discharge activity in the canola-based ester fluid compared to mineral oil.

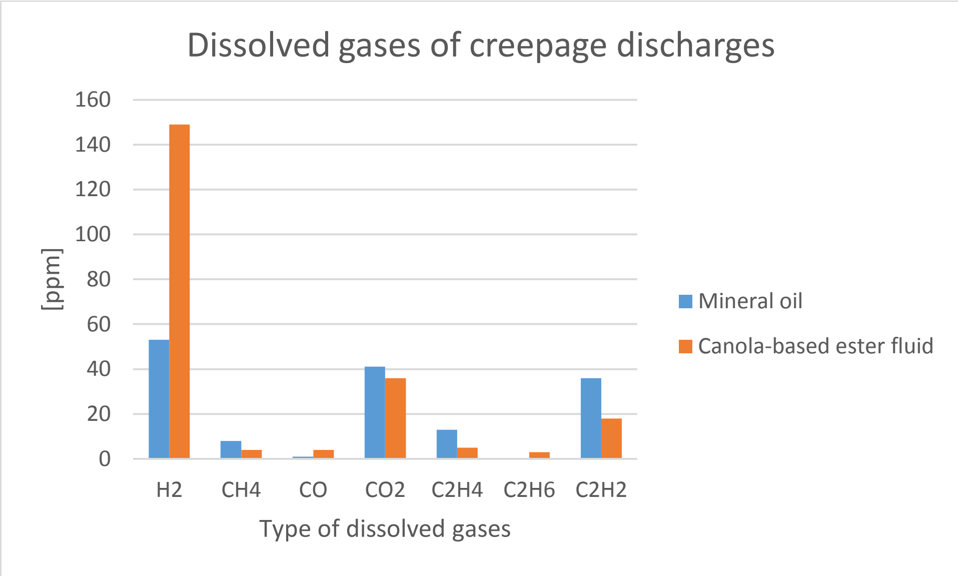

Figure 13: Dissolved gases from creepage discharges in canola-based ester fluid vs mineral oil

Even though creepage discharges are a type of partial discharges, they are categorised as a D1 fault according to IEC 60599 standard [20].

IEEE Key gas method: According to the IEEE key gas method, the creepage discharges were classified as a partial discharge in both the mineral oil and canola-based ester fluid due to the high quantity of hydrogen.

Ratios methods: The results of the IEC 60599 ratios is summarised in Table 12. It is observed in Table 13 that this method does not correctly identify the fault in the ester fluid due to the significantly high amount of dissolved hydrogen which affect the CH_4/H_2 ratio.

Table 13: IEC 60599 Diagnosis results of creepage discharges in canola-based ester fluid vs mineral oil

	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	
Mineral oil	2.7	0.15	13	low energy discharge
Canola-based ester fluid	3.6	0.02	1.6	n/a

Duval's triangles: Duval's Triangle 3 BIOTEMP was used to diagnoses the D1 fault of the canola-based ester fluid. The BIOTEMP Duval's triangle was chosen instead of the FR3 Duval's triangle since the canola-ester fluid is mainly oleic as is the case with the BIOTEMP ester fluid. The Duval's triangle correctly diagnosed the fault as a low energy discharge (D1) as shown in Figure 14, therefore, confirming the IEEE guide [25].

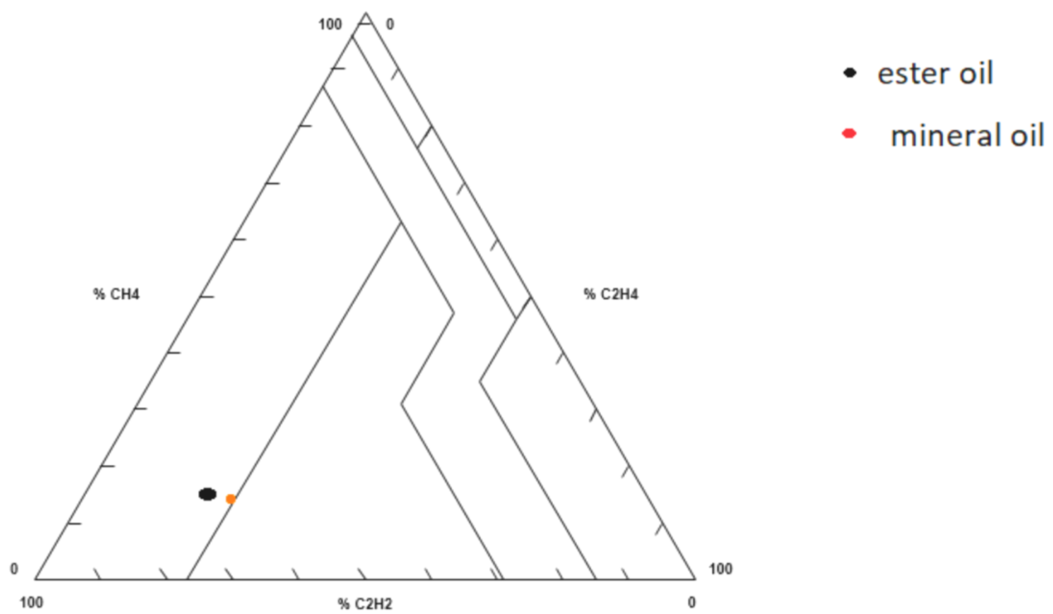

Figure 14: Duval's triangle fault diagnosis result of creepage discharge in canola-based ester fluid vs mineral oil

5.3 Chapter summary

Two studies were done in this work and they confirmed the IEEE guide for ester fluids when subjected to low energy discharges. As shown in Chapter 4 that there is limited knowledge about the DGA of high energy discharge in ester fluids, the present work proceeds towards the DGA of high energy discharges in canola-based ester fluid as presented in the next chapter.

Chapter 6 – DGA of High energy discharges of ester fluids

Chapter four has demonstrated the limited knowledge on the subject of DGA of high energy discharges in the guide for DGA of ester fluids. This chapter reviews the literature on the high energy discharge in ester fluids.

6.1 Literature on DGA of ester fluids under high energy discharge

In the literature, some studies have investigated the DGA of high energy discharge in ester fluids. The findings of these limited studies are summarised in Table 14.

Table 14: Summary of literature of DGA of ester fluid under high energy discharge

Author	**Type of ester fluid**	**Key Findings**
Xiang et al [7]	Camellia-based ester fluid	• Acetylene and ethylene are the key gases. • The classic Duval triangle is modified by substituting CH_4 with H_2 to correctly diagnose the high energy discharge fault as D2.
Ayalew et al [8]	Palm fatty acid ester oil and synthetic ester fluids compared to mineral oil	• Acetylene and hydrogen are the characteristic gases for D2 fault. • The quantity of total dissolved gases in synthetic ester are comparable with mineral oil. • The quantity of dissolved gases in mineral oil are almost twice as much as those in the natural ester fluid. • Carbon monoxide and carbon dioxide are dissolved in the natural ester fluid without the involvement of cellulose insulation. • Doernenburg ratio interpretation scheme correctly identifies the fault in the natural ester fluid

The studies summarised in Table 14 demonstrate that the soybean-based and palm fatty acid based-ester fluids have a similarity in the key dissolved gas whereby the gas is acetylene. However, the secondary key gas differs; it found to be ethylene in the soybean-based ester fluid whereas, it is found to be Hydrogen in the palm fatty acid based ester fluids. The similarities and differences in the gas characteristics of these ester fluids could be attributed to the fatty acid composition of these fluids. As shown in Table 15, the three ester fluid have different fatty acid composition; soybean is mostly composed of di-unsaturated acids, whereas, camellia ester fluid is composed of high quantities of mono-unsaturated acids, and palm fatty acid ester is composed of high quantities of saturated fatty acids [29].

These reported findings are limited to the two types of ester fluids, thus, reported they are required to be extended to other commercially available natural ester fluids. Therefore, this dissertation investigates the DGA of the commercially available canola-based ester oil under high energy discharge.

Table 15: Fatty acid composition of various natural ester fluids [29]

Type of natural ester fluid	**Saturated fatty acid [%]**	**Unsaturated Fatty Acids [%]**		
		Mono	**Di-**	**Tri-**
Soybean	14.2	22.5	51	12.3
Camellia	10.2	78.3	7.0	4.5
Palm fatty acid	49	40	10	1
Canola	7.9	55.9	22.1	11.1
Corn	12.7	24.2	58	0.7
Cottonseed	25.8	17.8	51.8	0.2
Peanut	13.6	17.8	51.8	0.2
Olive	13.2	73.3	7.9	0.6
Sunflower	10.5	19.6	65.7	-

6.2 Summary

While DGA of mineral oil is relatively a mature body of knowledge, the same however cannot be said about the DGA of ester fluids. In particular, the knowledge of DGA of ester fluids under high energy discharges is minimal and inconclusive. This dissertation aims to engage with this knowledge area in the context of the commercially available canola-based natural ester fluid.

Chapter 7 -Experimental methodology for studying DGA of high energy discharges in canola-based fluid

The previous chapter demonstrated that there is minimal and inconclusive knowledge on the DGA of ester fluids under high energy discharges. This dissertation aims to engage with this knowledge area by generating a high energy discharge fault in the laboratory and studying the gases dissolved in the canola-based ester fluid while using mineral oil as benchmark. This chapter presents the experimental methodology that is used in this regard.

7.1 Data specification of the canola-based ester fluid and mineral oil used in the experiment

The natural ester fluid that is investigated is the Midel eN1204 canola-based fluid. The mineral oil that is used as a benchmark for this work is the Engen Poweroil TO 1020 mineral oil. The basic chemical, physical and electrical properties of the investigated canola-based natural ester oil and mineral oil as specified in the manufacture's data sheets are summarized in Table 16 [30-31].

Table 16: Basic physical, chemical and electrical properties of canola-based natural ester oil and naphthenic mineral oil

Properties	**Test method**	**Canola oil (eN1204)**	**Mineral oil (Poweroil TO 1020)**
Appearance		Bright and clear	Light amber
Density at 20 °C [kg/cm^3]	ISO 3675	0.92	0.89
Viscosity at 40 °C [mm^2/s]	ISO 3104	37	12
Flash point [°C]	ISO 2719	> 260	> 135
Fire point [°C]	ISO 2592	> 350	
Pour point [°C]	ISO 3016	- 31	-40
Dielectric breakdown @ 2.5 mm gap [kV]	IEC 60156	> 75	70
Dissipation factor @ 90 °C	IEC 60247 or 61620	< 0.03	0.005
Corrosive sulphur	IEC 62535	Non-corrosive	Non- corrosive
Water content [mg/kg]	IEC 60814	50	10
Acid number	IEC 62021.3	≤ 0.04	0.01

7.2 Creating the high energy discharge

To the best of the author’s knowledge, a standardized circuit set-up for generating a high energy discharge in the laboratory does not exist. In the IEC 60599 standard, a high energy discharge in mineral oil-filled transformers is defined as: *a discharge in the oil with power follow-through* [20]. Moreover, the standard specifies that the typical transformer faults that are regarded as high energy discharges are; arcing of high local energy, flashover, tracking and etc. A review of the handful literature on generating high energy discharge is discussed in the next sub-section.

7.2.1 Techniques of generating high energy discharge in insulation, a snap literature review

In the work of Xiang et al. [7], a high energy discharge was produced by applying an A.C. voltage sufficient to cause a continuous breakdown on the ester fluid for 10 and 15 seconds using a point-plane electrode configuration. The resulting gases were correctly classified as a high energy fault by the more accurate Duval's triangle. In contrast, in the work of Ayalew et al. [8], the high energy discharge (arc discharge) was generated by applying a lightning impulse voltage on the insulation liquids (mineral oil, natural ester and synthetic ester fluids). But, the confirmation of the high energy discharge through the benchmark mineral oil was only correctly identified by a Dodernburg ratios method while the Rogers ratio method incorrectly identified the fault. In the CIGRE technical brochure on Advances in DGA interpretation [23], the Duval's triangle is considered the most accurate DGA diagnosis method in comparison to the ratios methods (including the Dodernburg method).

In this dissertation, the generation of high energy discharge for DGA purposes using A.C voltage sufficient to cause continuous breakdown is therefore conceptualised from the methodology of Xiang et al [6]. However, Xiang et al. [7], does not fully describe the voltage and current waveform characteristics of the high energy discharge. Therefore, a further snap literature review dealing with continuous A.C. breakdown in insulation oil was done. Abdi et al [34] deals with the energy of the continuous A.C. breakdown of mineral insulation oil under various gap-distances and various voltage ramps. In this dissertation, the electrode configuration and the gap distance of the experimental circuit set-up was conceptualised from Abdi et al [34] based on the nature of continuous A.C. voltage breakdown and the energy characteristics.

7.2.2 The circuit set up for creating high energy discharge in liquid insulation

The circuit set-up used for generating the high energy discharges is as shown in Figure 15. The circuit is composed of a 220 V/50 kV transformer, a 1.5 MΩ current limiting resistor, a test cell and measuring instruments. The transformer is used to provide the high voltage for the breakdown. The transformer is connected in series with a 1.5 MΩ distilled water resistor; the resistor is used for limiting the breakdown current and for the protection of the voltage supply. The high energy voltage and current are measured by a multi-channel digital oscilloscope through the voltage divider and current transformer respectively. The lists of the equipment used in the experimental set up is summarised in Table 17. In order to ensure accuracy of the measuring digital oscilloscope, the calibration function of the oscilloscopes' measuring probes was used prior to conducting the experiments.

Table 17: List of equipment used in the experiment

Equipment	**Rating**
Variac	220 V
Transformer	5 KVA, 220 V/50 kV
Current limiting resistor	1.5 MΩ
Multichannel digital oscilloscope	2GS/s
Current transformer	Sensitivity: 0.01V/A Max peak current: 50,000 A Droop rate: 3.0%/milliseconds

The test cell forms an important part of the work. It is designed such that it is transparent and sealable. The transparency requirement is to enable the observation of activities in the test cell during the experiments. Hence, the test cell is designed using a transparent Perspex material. Furthermore, the test cell is required to be sealable to prevent gas escape during the experiments and also to prevent the ingress of atmospheric air that could dilute with the fault gases. Therefore, the bottom of the test cell is sealed with aluminium base and rubber o-ring sealing while the top of the cell is sealed with bushing and also rubber o-ring sealings. The test cell is equipped with sphere-sphere electrodes of 13 mm diameters and a gap distance of 1 mm between the electrodes as done by Abdi et al [32]. It is worth noting, that this test cell is the same cell used in the DGA benchmark tests as detailed in Chapter 5. The detailed diagram of the experimental test cell is shown in Figure 16. An image of the entire laboratory set-up is shown in Figure 17.

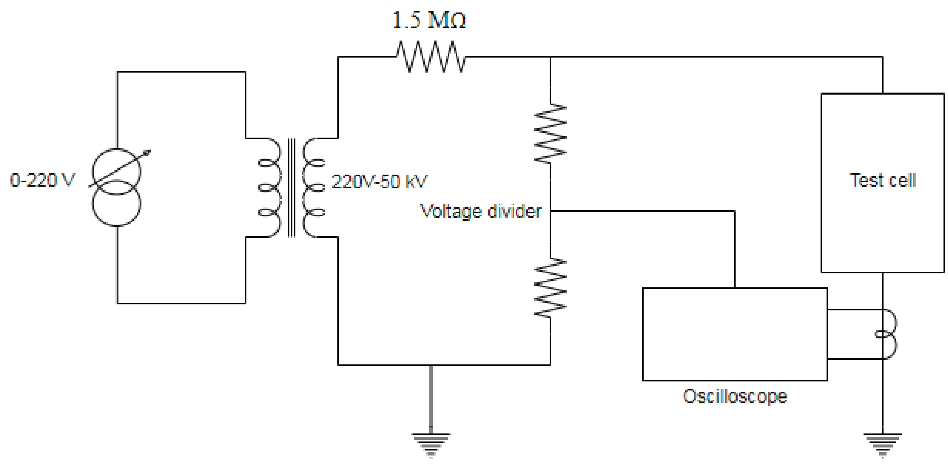

Figure 15: High energy discharge experimental schematic

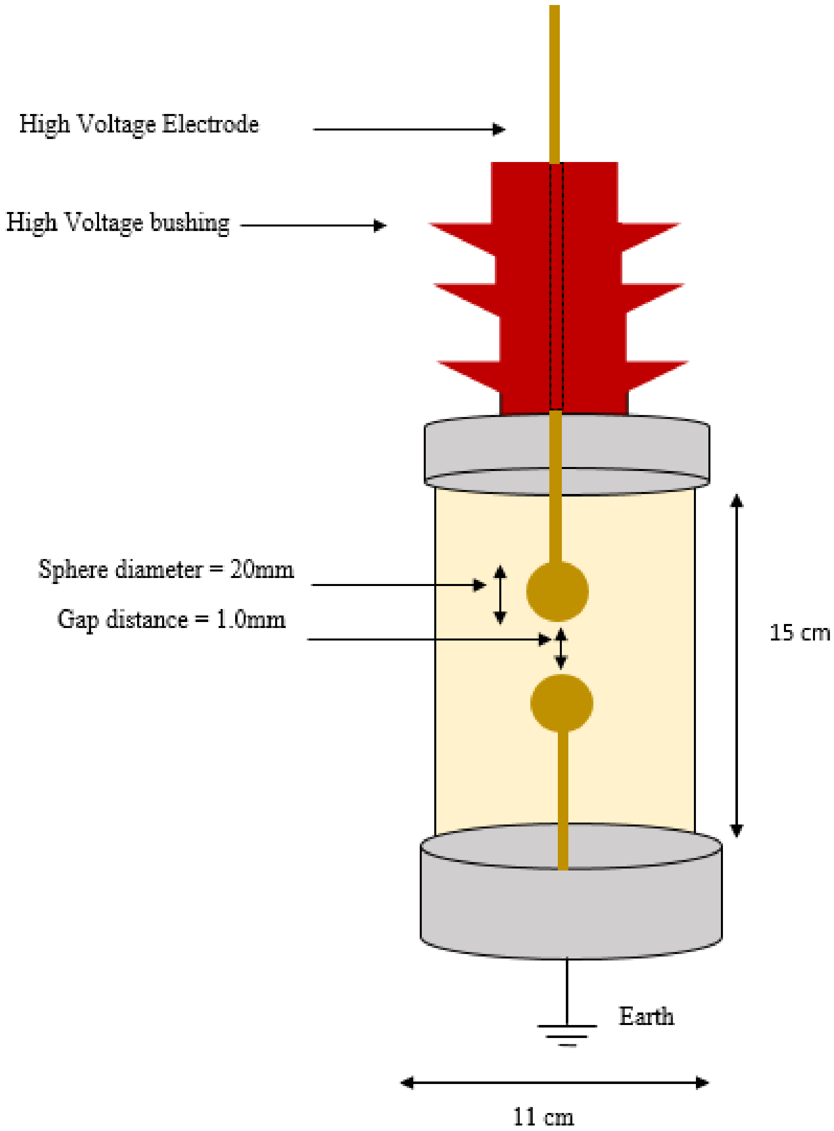

Figure 16: Detailed diagram of experimental test cell

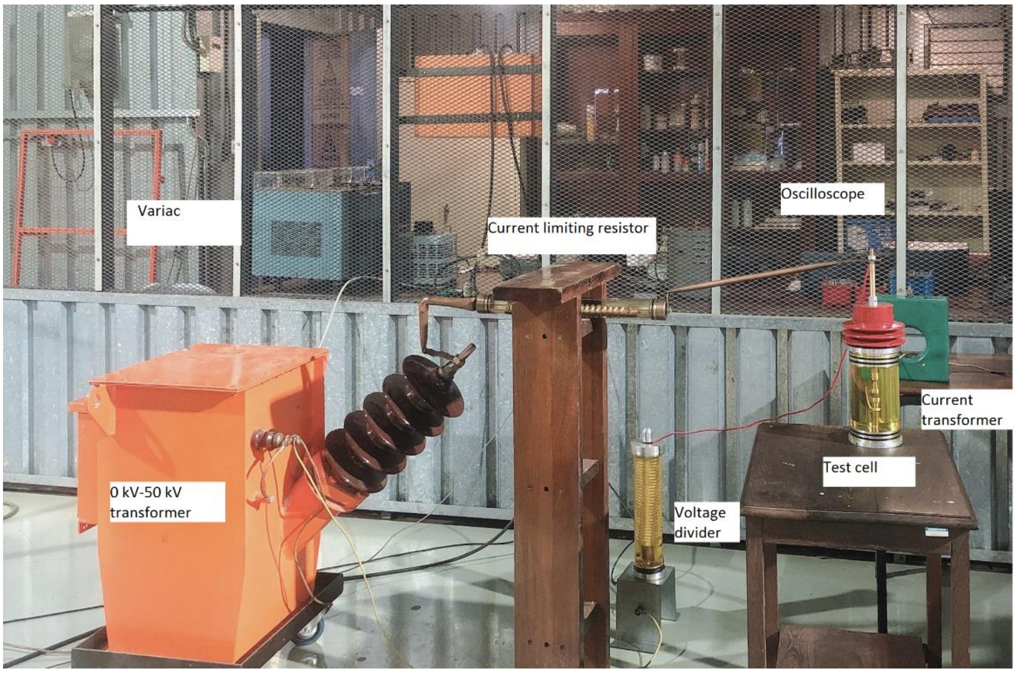

Figure 17: Image of high energy discharge circuit set up

7.3 Experimental procedure for high energy discharge

The experiments of the high energy discharge were conducted in the Wits University high voltage laboratory, under ambient atmospheric conditions of 25°C and 50 % humidity and at an altitude of 1740 m [33].

In order to ascertain that a high energy discharge is generated in the canola-based ester fluid, the high energy discharge experiment was first conducted in the mineral oil in order to benchmark the experimental methodology.

7.3.1 Voltage-Current characteristics

The high energy discharge was generated by applying the test voltage on the high voltage sphere electrode starting from zero until there is a continuous breakdown of the insulation liquid gap as done in the work of Xiang et al [7]. The continuous breakdown was sustained for a duration of at least fifteen seconds as also done by Xiang et al [7]. During the continuous breakdown activity, the breakdown voltage across the test cell and the current through the gap distance were measured, a snippet of the measured voltage and current waveform is shown in Figure 18. Figure

18 only demonstrates a snippet of the measured breakdown voltage and current; not the entire breakdown activity of fifteen seconds. This is due to the limitation of the digital oscilloscope that was used for the measurement which only captures triggered events. The fifteen seconds continuous breakdown event was observed visually and a snippet of the actual breakdown event is shown in Figure 19.

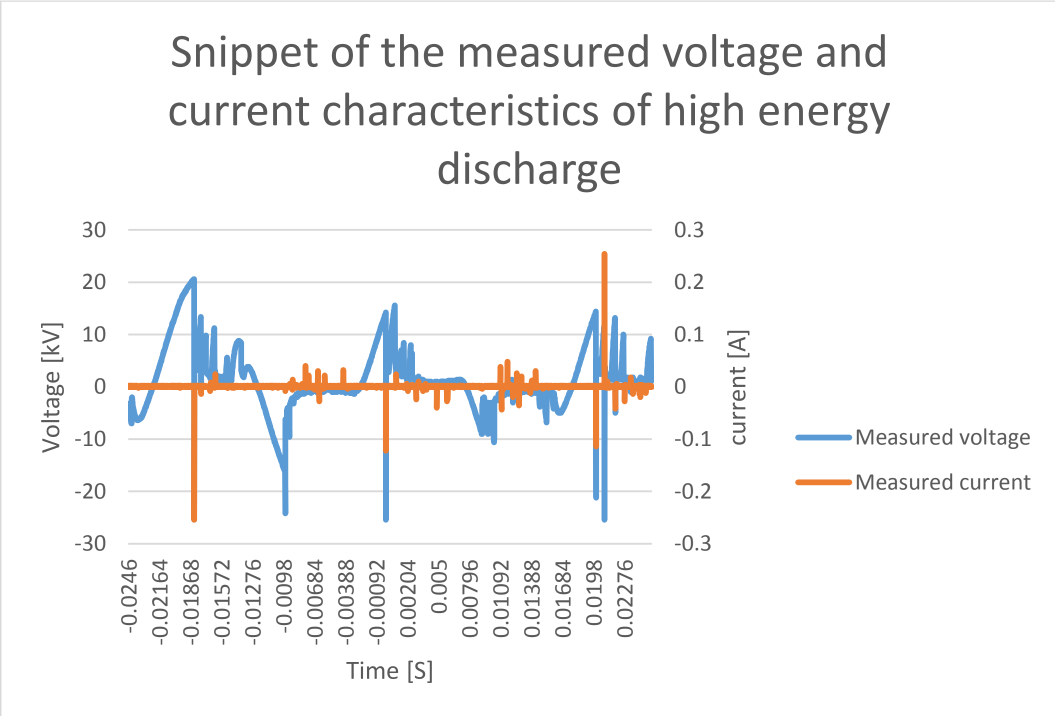

Figure 18: voltage and current waveform of the generated high energy discharge

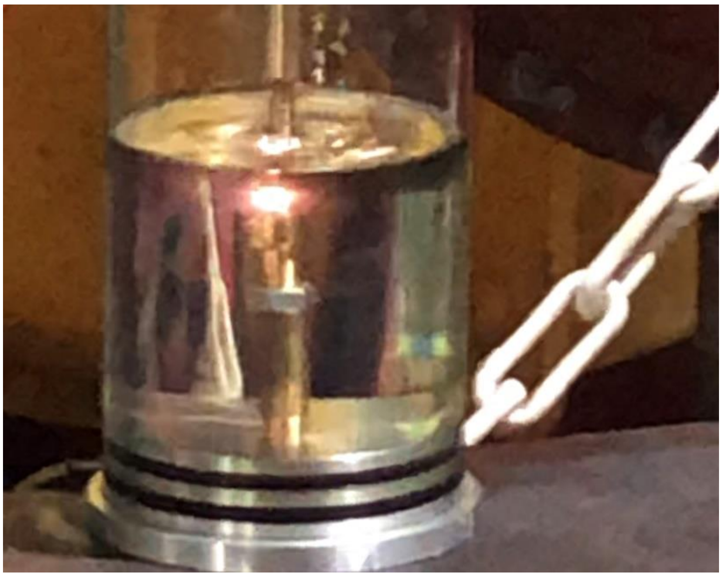

Figure 19: Snippet of observed continuous breakdown voltage activity

Based on the nature of the voltage and current relationship during the continuous discharge event, the measured high energy discharge characteristics of this work are comparable with those in the work of Abdi et al [32] as shown in Figure 20.

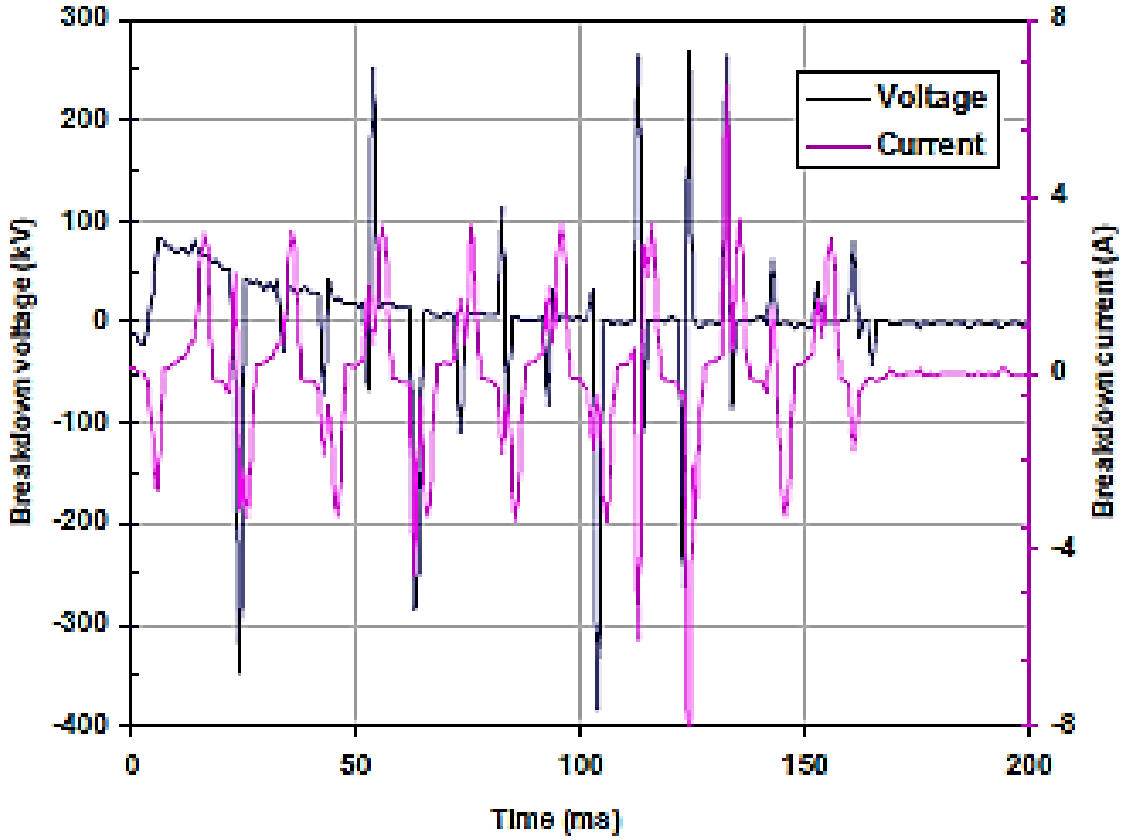

Figure 20: Voltage and current characteristic of continuous A.C breakdown from the work of Abdi et al [32].

After the fifteen seconds discharge duration elapsed, the test voltage was reduced to zero and the procedure was repeated three times before drawing out the insulation liquid sample for DGA purpose. The application of three shots of breakdown voltage was done to ensure that sufficient fault gases are generated in the insulation liquids.

After drawing out an insulation liquid sample, the test cell was filled with fresh insulation liquid and the high energy discharge experiment was repeated three times for both the mineral oil and the canola-based ester fluid. This was done to ensure repeatability of the experimental procedure.

The breakdown A.C. voltage sufficient to cause a continuous breakdown was recorded for each sample. The follow-through current of the continuous breakdown voltage was also recorded for each sample. These recorded breakdown voltage and current were used to compute power and subsequently an estimate of the energy of the high energy discharge fault as summarised in Table 18. The estimated energy in Table 18 was calculated using the measured voltage, measure current and the duration of the breakdown (15 seconds). This estimation of the energy in the fault assumes an ideal case whereby the breakdown voltage and current is constant for the 15 seconds duration of the discharge arc.

Table 18: Measured high energy discharge current and voltage

	Mineral insulation oil			**Canola-based ester insulation fluid**		
	Voltage [kV]	**Current [A]**	**Estimated energy [kJ]**	**Voltage [kV]**	**Current [A]**	**Estimated energy [kJ]**
Test 1	21	0.5	157.5	19.6	0.3	88.2
Test 2	21	0.4	120	18	0.2	81
Test 3	20	0.5	150	18.5	0.3	83.25

7.3.2 Observed physical evidence associated with high energy discharge

The physical evidence observed in service transformers that is associated with a high energy discharge fault includes the extensive carbonisation of the insulation oil [20]. During the laboratory experiments, when the continuous discharge was established in the insulation fluids, both the ester fluid and mineral oil experienced carbonisation as shown in Figure 21.

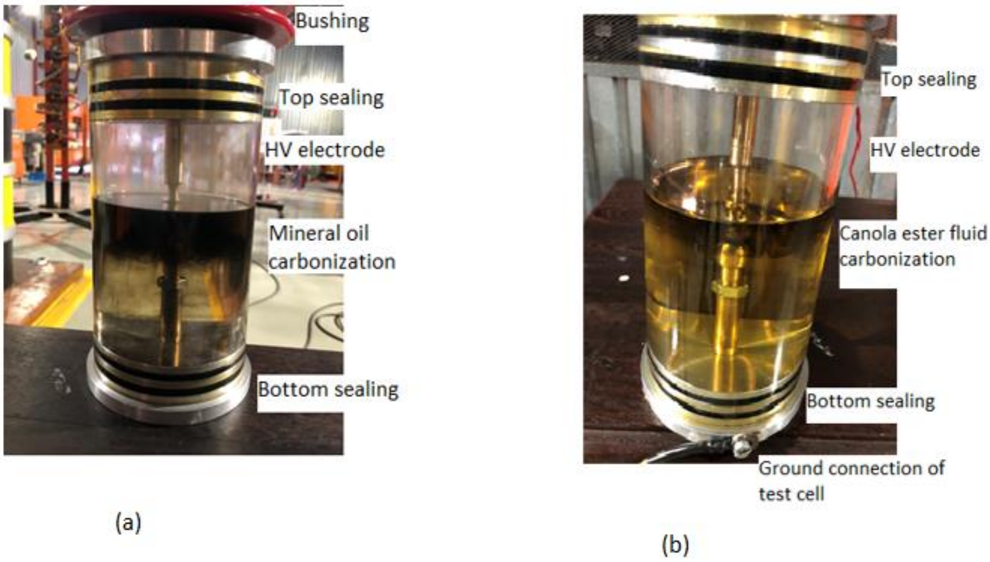

Figure 21: Observed carbonization: (a) mineral oil (b) canola-based ester fluid

7.4 The DGA procedure

Prior to conducting the experiments, the as-received samples of mineral oil and canola-based ester fluid were sampled for DGA analysis. The sampling of the as-received samples was done to establish a reference of the existing dissolved gases in the samples. The dissolved gases of the as-received samples are as summarised in Table 19.

The standard manual DGA procedure that is followed for the diagnosis of faults from in-service transformers is summarised in Figure 22. The procedure entails drawing out samples of the insulation oil from an in-service transformer, thereafter the oil sample to a DGA laboratory whereby the gases dissolved in the oil are extracted from the oil. The extracted gas mixture is then analysed by quantifying the individual dissolved gases. Lastly, DGA diagnosis methods are used to identify the type of incipient fault developing inside the transformer.

The procedure for performing DGA is required to be free of errors. Therefore, the DGA procedure has to be strictly as per the applicable standards. The oil sampling procedure is standardised in accordance with IEC 60475 standard [34]. The procedure of extracting gases from the oil and the analysis of the extracted gas mixture is detailed in IEC 60567 standard [35]. The diagnosis methods are documented in various documents including the IEC 60599 standard and the IEEE C57.104 guideline. The DGA procedure as detailed in the various standards and guidelines is summarised in the next sub-sections.

Table 19: gases in as-received samples of insulation fluids

Gases	**Mineral oil [ppm]**	**Canola-based ester fluid [ppm]**
H_2	0	20
CH_4	1	1
C_2H_4	0	1
C_2H_6	0	10
C_2H_2	0	0
CO	1	32
CO_2	293	407

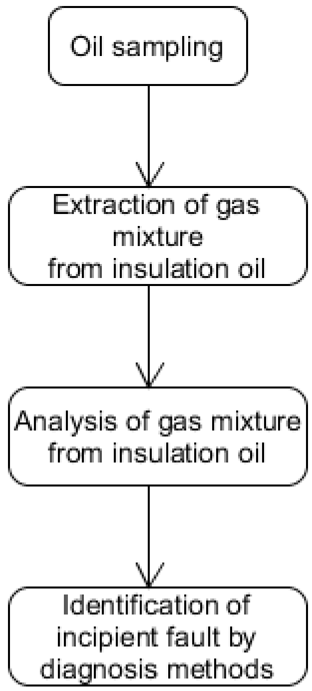

Figure 22: Summary of DGA procedure

7.4.1 Oil sampling procedure for diagnosis in power transformers

The procedure for sampling of insulation liquid from an oil-filled transformer is dependent on the used sampling equipment [34]. There are four types of sampling containers that can be used and these include; glass syringe, glass bottle, flexible metal bottle and glass/metal ampoule. The minimum volume of oil sample by any type of sampling container is required to be 25-100 ml. The sampling procedure for all container types is such that the formation of air bubbles in the sampled oil is avoided by allowing the oil to flow freely to the sampling container.

In the case of using transparent sampling containers, the containers should be protected from exposure to direct sunlight by wrapping them in an opaque material or placing them in a box during transportation.

After oil sampling, the samples are required to be transported to a DGA laboratory for gas extraction and analysis as soon as possible to avoid oxidation of the oil samples and gas losses. Sampling syringes are required to be placed in sealable boxes to avoid the possibility of oil movement which can lead to the formation of bubbles.

In this work, the sampling of the insulation liquids was conceptualised based on the IEC 60475 standard by using 50 ml glass sampling syringes which are equipped with a three-way valve [34]. The glass syringes were kept in a cardboard box with removable inner cardboard flaps that hold the barrel in place during transportation of the samples to the DGA laboratory.

7.4.2 Extraction of dissolved gases from insulation sample

The extraction of the gas mixture from the insulation oil is done following either of the three different methods; Toepler and partial degassing, stripping and headspace method [35].

Toepler and partial degassing: Vacuum extraction is accomplished according to two methods: multi-cycle method; Toepler and partial degassing is accomplished by vacuum extraction. In the Toepler method, a weighed volume of oil contained in the sampling syringe is drawn to a vacuum pump. The oil is exposed to the vacuum multiple times to ensure a maximum amount of extracted gases. Whereas, with the Partial degassing method, the oil sample is only exposed to a single pump cycle.

Stripping: In this method, the sampled oil is injected to the stripper device through a rubber septum. The dissolved gases are extracted by bubbling a carrier gas through a small volume of the sampled oil.

Headspace: In this method, the sampled oil is introduced to a vial that is in contact with a carrier gas. Analysis of dissolved gases is done by gas chromatography.

In this work, the extraction of gases was done in a certified laboratory of WEG transformer ™. The gases were extracted using the headspace method.

7.4.3 Analysis of the gas mixture

After the gas mixture is extracted from the insulation liquid, this mixture is required to be analysed in order to quantify the concentration of each gas. The analysis of the extracted gases is carried out using gas chromatograph instrument. This instrument analyses nine gases which include, hydrogen, oxygen, nitrogen, methane, ethane, ethylene, acetylene, carbon monoxide and carbon dioxide. The gas chromatography uses two detector columns (Porapak N and Molecular sieve), a thermal conductivity detector, flame ionization detector and a methanizer to analyse the available gases and determine their quantity. The gas sample is injected into the gas chromatography and travels to the separation columns which quantifies the amount of gases.

In the present work, the analysis of gases was accomplished in accordance with the headspace method and gas chromatography. The obtained results are presented in the next chapter.

7.5 Summary

Since the high energy discharge methodology is not clearly defined in the literature for both mineral oil and ester fluids, a high energy discharge fault was first generated on a mineral oil as a benchmark considering that the DGA of high energy fault is well established for the mineral oil. The benchmarked methodology was therefore reproduced for the high energy discharge on the canola ester fluid and the obtained results are presented in the next chapter.

Chapter 8 – High energy discharge Experimental Results and Analysis

The previous chapter detailed the experimental methodology for generating a high energy discharge in canola-based ester fluid. This chapter presents the results and analysis of the obtained dissolved gases.

8.1 Diagnosis of high energy discharge in mineral oil as a benchmark

The diagnosis of the benchmark high energy discharge fault in mineral oil is shown in Figure 23 and Table 20 and respectively. As shown in Figure 23 and Table 20, all the applied interpretation schemes correctly diagnose the high energy discharge in the mineral oil. This proves that the laboratory-generated faults is indeed a DGA high energy fault

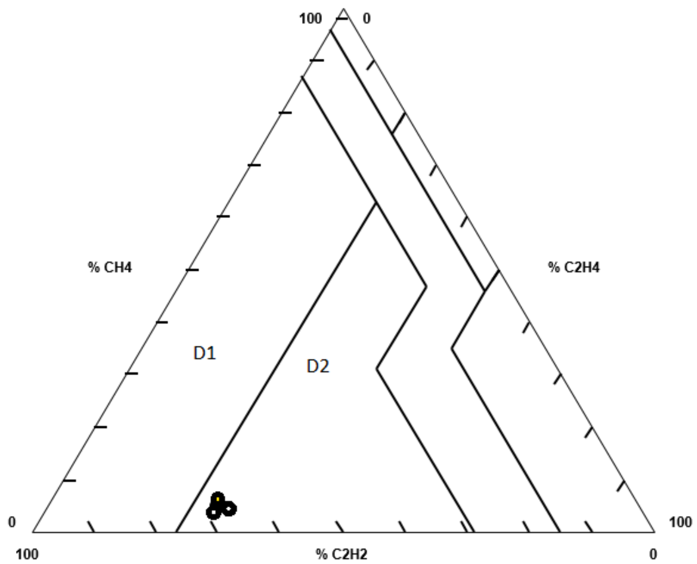

Figure 23: Results of Duval's triangle 1 diagnosis of D2 fault in mineral oil

Table 20: High energy discharge diagnosis of mineral oil

	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Diagnosis
Roger's ratios limits	0.1-3	0.1-1	>3	
Test 1	2.43	0.15	59.7	High energy discharge
Test 2	2.53	0.25	33.13	High energy discharge
Test 3	2.52	0.15	48.5	High energy discharge
IEC 60599 ratios limits	0.6-2.5	0.1-1	>2	
Test 1	2.43	0.15	59.7	High energy discharge
Test 2	2.53	0.25	33.13	High energy discharge
Test 3	2.52	0.15	48.5	High energy discharge

8.2 Dissolved gases characteristics of high energy discharge in canola-based ester fluid compared to mineral oil

The dissolved gases produced in the canola-based ester fluid in comparison to those in mineral oil are presented in Figure 24; where MO denotes mineral oil and NE denotes natural ester. The notable similarity in the dissolved gases characteristics between the ester fluid and mineral oil is the dissolved gases pattern.

In contrast, the signifiacant differences between the gas charactersistic of the canola-based ester fluid compared to mineral oil are as follows:

- The amount of Hydrogen and hydrocarbon gases (except C_2H_6) are low in the ester fluid compared to mineral oil.
- CO and CO_2 are produced in high quantities in the ester without the involvement of cellulose insulation.
- The ethane production in the ester fluid is higher than mineral oil.

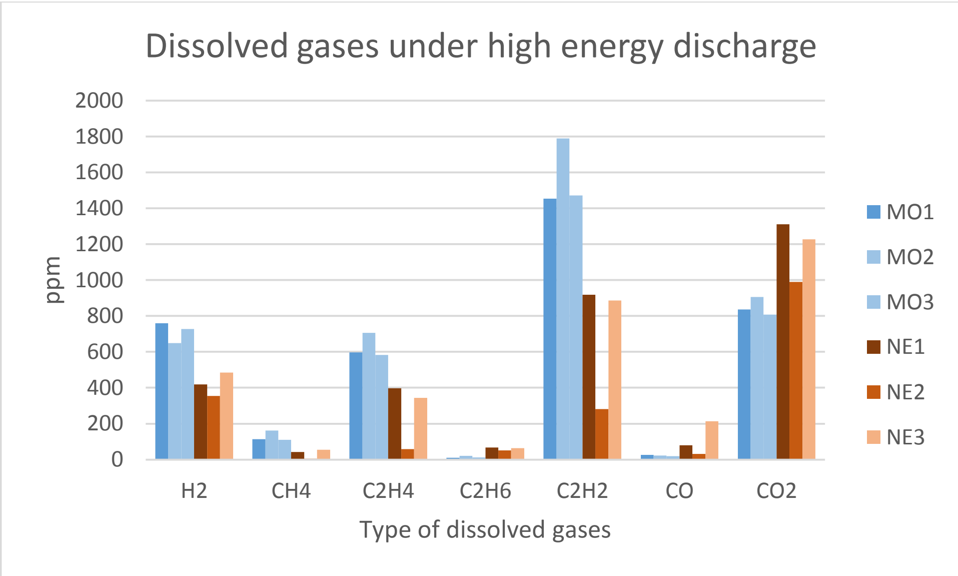

Figure 24: Comparison of dissolved gases in canola-based ester and mineral oil under high energy discharge

8.2.1 Similarities in the composition of generated gases in canola based ester and mineral oil under high energy discharge

It is observed in Figure 24 that the type of gases dissolved in the natural ester fluid are similar to those dissolved in the mineral oil. These gases include hydrogen, methane, ethane, ethylene, acetylene, carbon monoxide and carbon dioxide. These similarities are consistent with the knowledge in the IEEE guide for ester fluids and with the findings of Xiang et al and Ayalew et al [7-8, 19].

According to the decomposition of mineral insulation oil (discussed in Section 3.3), the gas formation pattern under a high energy discharge fault (D2) is known to include mainly H_2, C_2H_2, C_2H_4, CH_4 and small traces of C_2H_6. The dissolved gases that were generated in the canola-based ester fluid follow a similar pattern with the exception of the carbon oxides which were present in higher quantities in the canola-based ester fluid compared to mineral oil.

The similarities in the dissolved gases pattern of the mineral oil and the canola-based ester fluid are attributed to the chemical structures. As aforementioned in section 3.3., gases are formed as a result of the breaking of C-C and C-H chemical bonds to form radicals which recombine under complex reactions to form the low molecular hydrocarbons. Therefore, the chemical structure of the canola-based ester fluid also contains C-C and C-H bonds as was shown in Chapter 2, hence the type of dissolved gases generated in these insulation liquids are similar. However, there are also some notable differences in the gases dissolved in the canola-based ester fluid as discussed in the next sub-section.

8.2.2 Difference in the proportion of dissolved gases in canola-based ester fluid and mineral oil

The overall quantity of dissolved hydrocarbon gases in the canola-based ester fluid was observed to be lower than in the mineral oil. In the work of Fofana et al, the low gassing tendency of natural ester fluid compared to mineral oil is attributed to the chemical structure of the fluid [36]. Mineral oil is mainly composed of aromatic (unsaturated) molecules and small quantities of saturated hydrocarbons. And, depending on the refining process of mineral oil, in some cases, the unsaturated acids of the mineral oil can be lost [36]. Whereas, natural ester fluid is mainly composed of the ester group with saturated and unsaturated molecules. The high quantity of saturated and unsaturated acids of the natural ester fluid makes natural ester fluid more chemically stable and more uniform as compared to mineral oil [36]. Therefore, the breakdown of the chemical bonds in mineral oil is more favoured compared to natural ester fluids. Hence ester fluids generate low gases compared to mineral oil under the same fault conditions.

The stability of the canola-based ester fluid is further observed in the level of carbonization of the fluids as shown in Figure 21. It is apparent in Figure 21 that the level of carbonization in the canola-based ester fluid is less intense in comparison to the mineral oil.

8.2.3 Carbon monoxide and carbon oxide production in canola-based ester fluid under high energy discharge

In the DGA of mineral oil, the presence of CO and CO_2 in the dissolved gases is indicative of the thermal degradation of the solid cellulose insulation. [19-20]. However, in the canola-based ester fluid, it is observed that high quanitties of CO and CO_2 are produced in the ester fluid compared to the mineral oil. The high production of the carbon oxides in the ester fluid is attributed to the presence of the COO molecule in the chemical structure of the ester fluid as shown in Chapter 2; which does not exist in the mineral oil. According to the decomposition pathways of ester fluids, there are various decomposition reactions that can results in the production of the carbon oxides due to the presence of the COO molecule as sumarised in equations 2-7 [19].

$$RCOOH = CO_2 + RH \tag{2}$$

$$RCOOH = CO + RH \tag{3}$$

$$2RCOOH = CO_2+H_2O+RCOR \tag{4}$$

$$2RCOCH2R=2R_2+2CO+C_2H_4 \tag{5}$$

$$2R''CH=CO=2CO+RHC=CHR \tag{6}$$

$$CH_2=CHCHO=CO+C_2H_4 \tag{7}$$

These decomposition reactions that produce carbon oxides are further supported by the work of C.Xiang et al. [37] whereby unimolecular pyrolysis simulations are used to detail the complex decomposition reactions that results in the formation of dissolved gases in two types of natural ester fluid [37]. C.Xiang et al [37], details the decomposition reactions of both oleic (high quantities of mono-unsaturated) and linoleic acid (high quanities of di-unsaturated) ester fluids. According to these decomposition reactions as shown in Figure 25, there are two possible initial decomposition reactions that produce $C_{17}H_{33}COO$ and $C_{17}H_{33}CO$ radicals. The reaction products of $C_{17}H_{33}COO$ result in the formation of CO_2 + $C_{17}H_{33}$. Hence, the high quantities of CO_2 exist in canola-based ester fluid. The reactions of the $C_{17}H_{33}CO$ radical result in the formation of $C_{16}H_{31}$(radidcal) + CO. Hence the high quanitties of CO in the ester fluid in comparison to mineral oil.

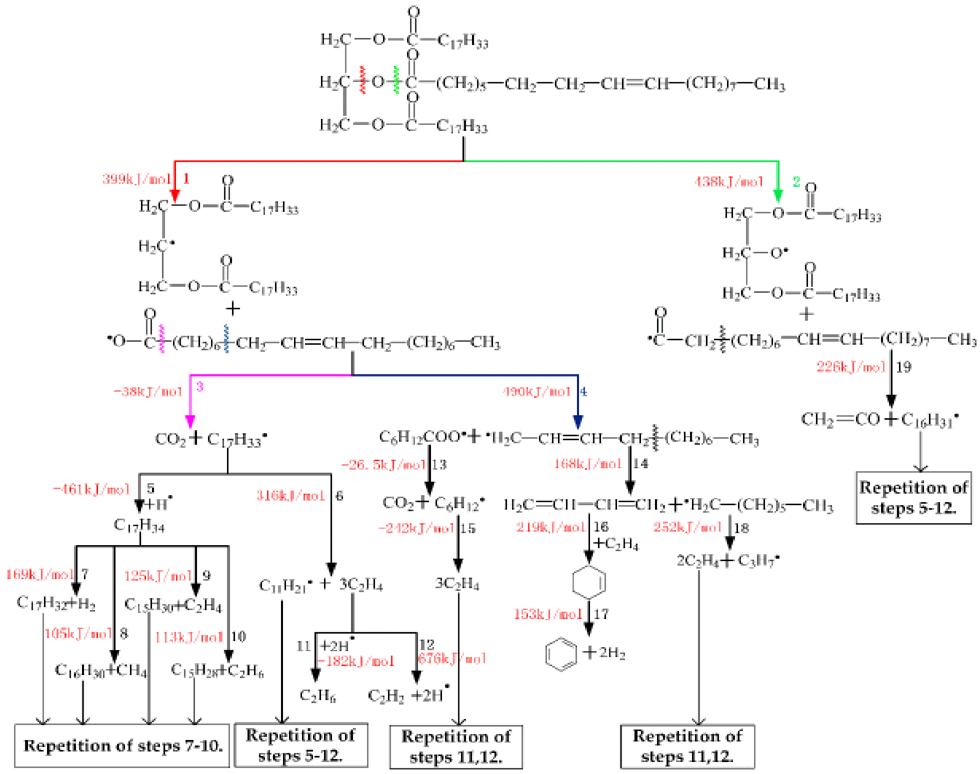

Figure 25: Decomposition pathway of linoleic ester fluid, as adapted from [37]

8.2.4 Ethane production

The production of ethane in natural ester fluids is a widely investigated topic in literature. Ethane is widely known to be a characteristic gas of stray gassing of linolenic ester fluids [25]. Moreover, IEEE guide for interpretation gases in ester fluids, specifies that since rapeseed(canola)-based natural ester fluid contains higher amounts of linolenic, then the production of ethane is favoured.

8.3 Diagnosis of high energy discharge in canola-based ester fluid

The overall dissolved hydrocarbon gases in the canola-ester fluids are lower than those in mineral oil. This implies that the typical values of gases which are normally indicative of a developing fault require modification for use in canola-based fluid. The identification of the high energy discharge in the canola ester fluid using the traditional diagnosis methods is discussed in the next sub-section.

8.3.1 Key Gas method for diagnosing high energy discharge in canola-based ester fluid

The key dissolved gas in the canola-based ester fluid under the high energy discharge fault was found to be acetylene, this is consistent with key of mineral oil. Therefore, this diagnosis method can be used for this type of fault in the canola-based ester fluid.

As discussed in chapter 3, DGA in mineral oil-filled transformer is also used to diagnose faults involving the pressboard insulation. The gases indicative of pressboard fault are carbon monoxide and carbon dioxide. The findings of this work indicate that the canola-based ester fluid produces high quantities of carbon oxide compared to mineral oil without the involvement of cellulose. This implies that the diagnosis of pressboard related faults require modification for canola based-filled transformers.

8.3.2 Rogers ratios diagnosis of high energy discharge in canola-based ester fluid

The results of the diagnosis of the high energy discharge in the canola based-ester fluid using the Rogers ratios are summarised in Table 21. The results demonstrate that this method can correctly diagnose two of the three samples of the canola-based ester fluid. The incorrectly diagnosed sample failed due to the C_2H_2/C_2H_4 and the CH_4/H_2 ratios which are not within the required boundaries. This was a result of the significantly low amount of C_2H_4 and CH_4 that is dissolved in the canola-based ester produced. The low quantity of ethylene and methane in the sample could be attributed to possible gas loss during the transportation of insulation liquid samples to the DGA laboratory.

Since two of the three insulation fluid samples were correctly diagnosed by the Roger's ratios method, this method can be used (with caution) to diagnose the high energy discharge fault in the canola-based ester fluid.

Table 21: Roger's ratios results of canola-based ester fluid

Fault type	**C_2H_2/C_2H_4**	**CH_4/H_2**	**C_2H_4/C_2H_6**	**Diagnosis**
High energy discharge requirements	**0.1 – 3**	**0.1 – 1**	> **3**	
Canola-based ester fluid results	2.3✓	0.1 ✓	5.83✓	High energy discharge
	4.7 X	0.01 X	1.15✓	No diagnosis
	2.57✓	0.11✓	5.34✓	High energy discharge

8.3.3 IEC 60599 Ratios diagnosis of high energy discharge in canola-based ester fluid

Again, for the IEC 60599 ratios, the diagnosis of the high energy discharge in the canola-based ester fluid is correctly diagnosed in two of the three samples as shown in Table 22. As mentioned in the section 8.3.2, the incorrectly diagnosed sample failed due to the C_2H_2/C_2H_4 and the CH_4/H_2 ratios which are not within the required boundaries. Therefore, in average this diagnosis method can be used (with caution) to diagnose the high energy discharge fault in canola based-ester fluid.

Table 22: Results of IEC 60599 ratios of canola based-ester fluid

Fault type	**C_2H_2/C_2H_4**	**CH_4/H_2**	**C_2H_4/C_2H_6**	**Diagnosis**
High energy discharge requirements	**0.6 – 2.5**	**0.1 – 1**	**> 2**	
Canola-based ester fluid results	2.3✓	0.1 ✓	5.83✓	High energy discharge
	4.7 X	0.01 X	1.15✓	No-diagnosis
	2.57✓	0.11✓	5.34✓	High energy discharge

8.3.4 Duval's triangles diagnosis of high energy discharge in canola-based ester fluid

The newly developed Duval's triangles for diagnosis of ester fluids were used to evaluate the DGA results of the canola-based ester fluids. Both the triangles for BIOTEMP natural ester and FR3 natural ester were evaluated as shown in Figure 26 and 27 respectively. It is interesting to observe that both Duval's triangles yielded the same diagnosis outcome. Two of the three samples were correctly diagnosed as D2 (high energy discharge) fault as in the case of the ratio methods. The third sample was diagnosed as a D1 (low energy discharge) fault. It is worth noting that the Duval triangle diagnosis method is a closed system hence a fault is always diagnoses, hence the sample that could not be diagnosed by the ratios methods was diagnosed by the Duval's triangle method. Therefore, in average this diagnosis method can correctly diagnose the high energy discharge in canola-based ester fluid.

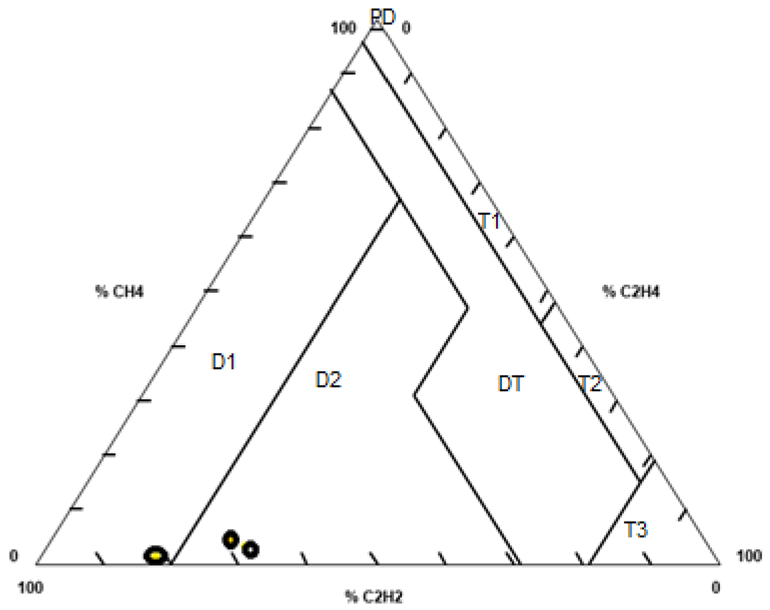

Figure 26: Results of Duval's triangle 3 (BIOTEMP) of canola-based ester fluid

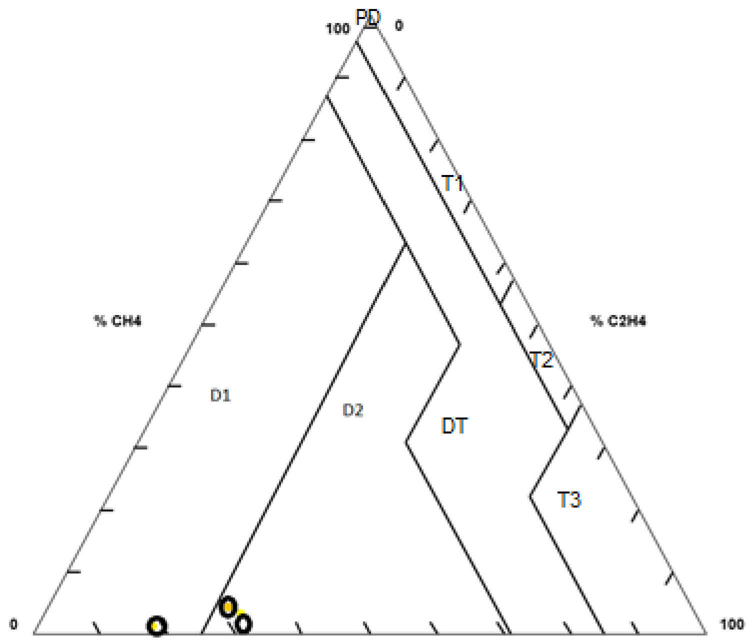

Figure 27: Results of Duval's triangle 3 (FR3) of canola-based ester fluid

Figure 27: Duval's triangle 3 FR3 results

8.4 Summary

Even though there is a difference in the molecular structure of canola-based ester fluid to mineral oil, the results of high energy discharge demonstrate that there are similarities in the composition of dissolved gases generated in these insulation liquids. But, there are also notable differences which include; high production of carbon oxides in the canola-based ester fluid without the involvement of cellulose insulation, notable ethane production in the ester fluid and overall less production of dissolved gases in the mineral ester fluid. The application of the commonly used DGA interpretation methods demonstrate that these method can be applied to canola-based ester fluid for the diagnosis of a high energy discharge fault but with caution.

Chapter 9 – Conclusions and Recommendations

9.1 Conclusions

This dissertation has presented an investigation into the DGA of canola-based ester fluid when subjected to a high energy discharge. The finding of this work reveal that the composition of dissolved gases in the canola-based ester fluid is comparable to that of mineral oil under the same high energy discharge fault. These gases include; acetylene, hydrogen, ethylene, methane, carbon dioxide and carbon monoxide. The similarity in the composition of the dissolved gases is attributed to the presence of the carbon-hydrogen molecules that are present in both mineral oil and ester fluids.

Even though there are similarities in the composition of the dissolved gases, there were also notable differences observed in the canola-based ester fluids. These differences include; overall low quantities of dissolved hydrocarbon gases, the generation of ethane and the high quantities of carbon oxides in the ester fluid.

The relatively low quantity of dissolved hydrocarbon gases in the canola-based ester fluid under the high energy discharge compared to mineral oil implies that the typical values which are normally used for early identification of a fault are required to be modified for canola-based ester transformers.

In terms of the diagnosis of the high energy discharge by the key gas method, , the main key gases produced in the canola-based ester fluid under this fault was found to be acetylene and hydrogen as is the case in mineral oil. In conventional mineral oil-based diagnosis methods, the presence of carbon dioxide is normally indicative of fault that involves cellulose insulation. Thus, the relatively high carbon oxides generated in the canola-based ester fluid without the involvement of cellulose could results in incorrect fault identification. Therefore, in canola-based ester fluid, the presence of carbon dioxide cannot be only associated with a cellulose insulation fault.

For the IEC 60599 ratios, Rogers's ratios and Duval's Triangle three methods, the high energy discharge fault was correctly diagnosed in two of the three samples. In the one sample, the high energy discharge was not correctly diagnosed, possible due to gas loss during the transportation of the samples to the DGA laboratory. Therefore, the ratios methods and Duval's triangle three can be used in canola fluid-filled transformers.

9.2 Recommendations

In this work, the high energy discharge fault was generated by applying A.C. voltage that is sufficient to cause continuous breakdown for 15 seconds. The breakdown event could not be captured for the entire duration since the measuring instrument used was a digital oscilloscope. Thus, it is recommended that for future work, an advanced measuring instrument for measuring the breakdown voltage and current for the duration of the continuous breakdown is used in order for the entire breakdown activity to be captured.

Also, the limitation of the digital oscilloscope in measuring the entire continuous breakdown event, resulted in challenges with the calculation of the energy contained within the fault. Therefore, for future work it is recommended that in addition to the use of an advanced measuring instrument, the energy contained in the fault is calculated using more accurate mathematical methods, for example, the Riemann's sum.

The high energy discharge faults in this work was only limited to a canola-based ester fluid. This work can be extended to other types of ester fluids to ensure that the behaviour of different commercially-available ester fluids is fully understood.

The breakdown voltage used in this work was limited to the range of 20 kV – 30kV. However, in-service transformers are exposed to even higher voltages. Therefore, for future work, higher voltages which are in the range of in-service transformers are recommended to be used. This is to ensure that the phenomena's associated with the high energy discharge are fully studied.

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Appendix A – Author’s Publications

This Appendix contains the author’s publications presented in the 9th CIGRE Southern Africa Regional conference and the IEEE 2020 SAUPEC conference.

A1: CIGRE published paper

9th CIGRE Southern Africa
Regional Conference
1st – 4th October 2019
Johannesburg, South Africa

Investigation of the application of Dissolved Gas Analysis (DGA) in canola-based natural ester oil under arcing fault

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SUMMARY

The objective of this work is to investigate the application of Dissolved Gas Analysis (DGA) in canola-based natural ester under arcing fault. The well-established DGA tool has been optimised for mineral oil-filled power transformers but ester oil is set out to replace mineral oil due to its excellent environmental properties. DGA is a diagnostic tool used in power transformers to detect incipient faults. The detection of incipient faults enables timeous scheduling of preventative maintenance and hence prevention of transformer damage. This in turn ensures that power transformers are resilient against possible damage from faults.

The investigation in this work is done by inducing an arcing fault to canola-based ester oil and mineral oil. The arcing fault is generated by an AC voltage applied to a point-sphere electrode configuration. The types and quantities of the dissolved gases in the oil are analysed using gas chromatography. DGA interpretation schemes; IEEE key gas, IEC 60599, Rogers ratios and Duval triangle are applied to the dissolved gases to evaluate the ability of these interpretation schemes to identify the arcing fault. The findings of this work indicate that IEEE key gas method, IEC 60599 ratios and Duval triangle can correctly diagnose an arcing fault in canola-based ester oil. This finding will aid in shading light on the possibilities of directly applying the existing mineral oil based DGA in ester oil filled transformers. The availability of a DGA tool for ester oil filled transformers will ensure that the future power transformers are well equipped with condition monitoring tools which aid in power infrastructure resilience.

KEYWORDS

Arcing fault, Dissolved Gas Analysis, Ester oil, Interpretation schemes

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1 INTRODUCTION

Power transformers are the most crucial and expensive equipment in the transmission and distribution network. The leading cause of transformer failures has been found to be a results of insulation failure [1]. It is therefore crucial for insulation to be assessed to detect any abnormalities and developing faults inside the transformer. Dissolved Gas Analysis (DGA) is a diagnostic tool used in oil-filled power transformers to detect incipient faults developing inside the transformer [2]. DGA is based on the analysis and interpretation of dissolved gases in insulating oil. Gases are produced in transformer insulation oil in service due to thermal, electrical and chemical stresses which degrade the insulation, resulting in the production of low molecular gases [3]. The low molecular hydrocarbon gases are dependent on the chemical composition of the insulating oil. Knowledge of the type & quantity of dissolved gases allows for the type of developing fault to be identified using DGA interpretation schemes. The faults detectable by DGA are; partial discharge, thermal faults (of different temperature ranges) and arcing. The ability to identify incipient faults is important for preventative maintenance that ensures proactive actions are taken timeously to avert transformer damage and failure.

Mineral oil has been widely used in power transformers for decades but the oil has environmental and safety limitations since it is non-biodegradable, toxic and highly flammable [3]. Ester oil has been found to be an alternative insulating oil since it is fully biodegradable, fire safe and has additional advantages which include moisture solubility and the ability to operate at higher temperatures [4-5]. The existing DGA tool has been characterized for mineral oil-filled transformer. The introduction of ester oil in power transformers raises the need for verifying if the mineral oil-based DGA tool can be utilized in ester-filled power transformers. This work investigates the application of the mineral oil-based DGA tool in canola-based natural ester oil under arcing fault. The application of DGA in canola-based ester oil is lacking in literature. This is done by evaluating the ability of the well-established DGA interpretation schemes to identify the arcing fault in ester oil.

2 DGA INTERPRETATION SCHEMES

DGA is based on the analysis and interpretation of dissolved gases in the insulating oil. The interpretation of the dissolved gases results in the identification of the type of incipient fault developing inside the transformer. There are various DGA interpretation schemes that have been well characterized for mineral oil-filled transformers using field data. The commonly used interpretation schemes are; IEEE key gas, IEC 60599 ratios, Rogers ratios and Duval triangle [6]. Each of the analysis and interpretation method is reviewed in the following sub-sections.

2.1 IEEE Key Gas

The IEEE Key Gas interpretation scheme is based on the identification of the dominating dissolved gases [7, 8]. The key gas is identified as the dissolved gases with the highest percentage concentration. There are four types of faults that are identified using this interpretation scheme as summarized in Table 1.

Table 1 : IEEE Key gas interpretation scheme

Type of fault	Key gas
Arcing	Acetylene and hydrogen
Partial discharge	Hydrogen
Oil overheating	Ethylene (high temperature), methane and hydrogen (low temperature)
Cellulose overheating	Carbon monoxide

2.2 IEC 60599 Ratios

The IEC has published a standard for the interpretation of incipient faults in power transformers based on DGA. The standard is based on interpreting incipient faults using three gas ratios from the quantity of five dissolved gases. The three ratios are C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6. This interpretation scheme can detect six types of incipient faults based on the values of the gas ratios as summarized in Table 2 [9].

Table 2 : IEC 60599 faults classification

Fault code	Fault type	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
PD	Partial discharge	Not significant	< 0.1	< 0.2
D1	Discharge of low energy	> 1	0.1 - 0.5	> 1
D2	Discharge of high energy	0.6 - 2.5	0.1 - 1	> 2
T1	Thermal fault (T < 300 °C)	Not significant	> 1	< 1
T2	Thermal fault (300 -700 °C)	< 0.1	> 1	1-4
T3	Thermal fault (T > 700 °C)	< 0.2	> 1	> 4

2.3 The Rogers Ratios method

The Rogers Ratios interpretation scheme uses four gas ratios from five gases (H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2) to identify the type of incipient fault [10]. The four gas ratios are C_2H_2/C_2H_4, CH_4/H_2, C_2H_4/C_2H_6 and C_2H_6/CH_4. The incipient faults detected by this interpretation scheme are summarized in Table 3.

Table 3 : Rogers Ratios fault classification

Fault type	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
Normal condition	< 0.1	> 0.1 - 1	<1
Partial discharge	< 0.1	< 0.1	< 1
Arcing	0.1 - 3	0.1 - 1	> 3
Thermal fault (T < 300 °C)	< 0.1	> 0.1-1	1 - 3
Thermal fault (300 -700 °C)	< 0.1	> 1	1 - 3
Thermal fault (T > 700 °C)	< 0.2	> 1	> 3

2.4 Duval Triangle

The Duval Triangle interpretation scheme uses a triangular graphical representation of three gases (C_2H_4, CH_4, and C_2H_2) to deduce the type of fault as shown by Figure 1 [6-8]. The relative percentage of the three gases is computed to identify the type of faults. The criteria used for the classification of faults are given in Table 4.

Figure 1 : Duval triangle as adapted from [7]

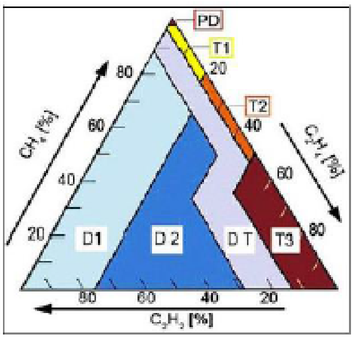


Table 4 : Duval triangle fault classification

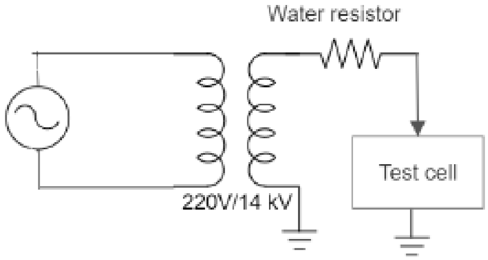
Duval triangle fault code	Fault type	% CH_4	% C_2H_2	% C_2H_4
PD	Partial discharge	98		
T1	Thermal fault of temperature less than 300 °c		< 4	< 20
T2	Thermal fault of temperature range of 300 – 700 °C		< 4	20 -50
T3	Thermal fault of temperature range of 300 – 700 °C		< 15	> 50
D1	Low energy discharge (sparking)		> 13	< 23
D2	High energy discharge (arcing)		13-29	23 - 38
			> 29	> 23
DT	Mix of thermal and electrical faults	Rest area		

3 EXPERIMENTAL METHODOLOGY

3.1 Arcing experimental set-up

The arcing fault was produced by simulating a A.C breakdown voltage using the circuit set-up shown in Figure 2. A point-sphere electrode configuration with a gap distance of 25 mm was used. The diameters of the point and sphere electrode are 50 μm and 20 mm respectively. The electrodes were immersed in one litre of insulating oil in a tightly sealed test cell. A current limiting resistor was incorporated in the circuit to limit short circuit currents during the gap flashover.

Figure 2 : Breakdown voltage circuit set-up



The A.C voltage was increased in steps of 5 kV from 0 kV until breakdown occured. This procedure was repeated 50 times to ensure that sufficient amount of dissolved gases is generated in both mineral and ester oil.

3.2 DGA sampling and analysis

The sampling of the mineral and ester oil for gas analysis after 50 voltage breakdowns was done using specialized 50 ml glass syringes. The glass syringes ensure minimized gas loss during transportation of oil to DGA laboratory.

The dissolved gases were analyzed using gas chromatography to determine the type and quantity of the dissolved gases.

4 RESULTS AND ANALYSIS

4.1 A.C breakdown voltage

The average breakdown voltage of mineral and ester oil was found to be 42 kV and 63kV respectively. These results indicate higher dielectric strength of ester oil than mineral oil.

4.2 Dissolved gases

The results of the five characteristic gases dissolved in mineral and ester oil are presented in Figure 3. The results indicate that mineral oil produces higher quantities of dissolved gases compared to ester oil. This finding corresponds to the findings of Bandara et al [3] and Ghani et al [11] who investigated the dissolved gases in mineral oil versus sunflower-based and palm-based ester oil respectively.

A2: SAUPEC publication

Dissolved Gases Analysis of canola-based ester oil under creepage discharge

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***Abstract*— The objective of this work is to investigate the Dissolved Gases Analysis (DGA) of canola-based ester oil under creepage discharge. DGA is a reliable diagnostic tool used in power transformers to detect incipient faults developing inside the transformer. The detection of incipient faults enables early scheduling of preventative maintenance and hence prevention of transformer damage. Recently, natural ester oils have been introduced to power transformers as an alternative oil. The application of natural ester oils in power transformers requires a guideline for the application of DGA in this type of oil. The creepage discharges are generated by applying 28 kV to a needle-plane configuration configured at an acute angle. The dissolved gases result reveal that similar gases are generated in the ester and mineral oil while the quantity of dissolved gases is high in the ester oil than the mineral oil. The key dissolved gas was found to be hydrogen. The Duval's triangle and the IEEE key gas diagnostic technique correctly identify the fault while the IEC 60599 fails to identify the fault. The IEC 60599 requires modifications for use in transformers filled with canola oil.**

Keywords—Canola-based natural ester oil, Creepage discharges, Dissolved Gas Analysis

I. Introduction

Power transformers are equipped with three dimensional insulation system that comprises insulation oil and cellulose based pressboard [1]. Partial discharges normally occur in the insulation systems of transformers. Power transformers experience two main types of partial discharges; creepage discharges in the pressboard-oil interface and corona discharges in the oil. Creepage discharges develop on the oil-pressboard interface [2]. The development of creepage discharges on the oil-pressboard interface result in the development of a conducting path on the surface of the pressboard (in the form of carbonized white marks) which subsequently degrades the pressboard material by reducing its dielectric and mechanical strength [3].

Dissolved Gas Analysis (DGA) is a diagnostic tool used to detect incipient faults developing inside a power transformer [1]. DGA is based on the analysis of gases dissolved in the oil as a result of electrical and/or thermal stress that degrades the oil and produce gases. The early detection of incipient faults allows for scheduling of maintenance and subsequently the prevention of transformer failure and damage. The six categories of faults detectable by DGA according to IEC 60599 standard are partial discharges (corona type), low energy discharges, high energy discharge, low thermal faults, medium thermal faults and high thermal faults [4]. DGA has been developed for mineral oil-filled power transformers. Natural ester oil is considered an alternative to mineral oil since mineral oil is highly flammable and non-biodegradable. The introduction of natural ester oil as transformer insulation liquid raises the need to evaluate if DGA can be used for this alternative insulation oil given the chemical difference in mineral and natural ester oil.

Mineral oil is made from fossil oil and consist of carbon-hydrogen bonds as shown in Fig. 1 [5]. Natural ester oil is made from the esterification reaction of alcohol and fatty acid [5]. The oil contains saturated and unsaturated fatty acid groups connected to glycerol molecule as illustrated by Fig. 2.

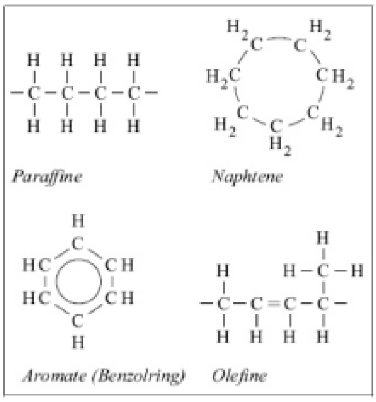

Fig. 1: Chemical structure of mineral oil as adapted from [4]

Studies have been done to investigate the dissolved gases of natural ester oils under partial discharges. The work of Xiang et al and Muhamad et al have focused on the DGA of soy-based and camellia based ester [6, 7]. Susilo et al and K. Azmi et al investigated the DGA of palm-based oil [8, 9]. The dissolved gases from the different types of natural esters have been found to differ in composition and quantity in comparison to mineral oil. The difference in the composition and quantity can be attributed to the difference in the

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chemical structures of different natural esters as summarised in Table I [10]. This work therefore, investigates the DGA of canola-based ester oil under creepage discharges using mineral oil as a benchmark. The DGA of canola-based natural ester oil is investigated by studying the type of dissolved gases, the concentration of the gases and the generation rate of those gases in comparison to mineral oil.

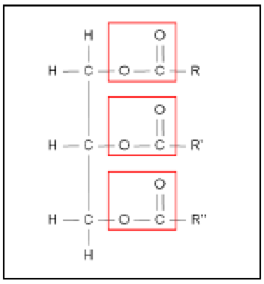

Fig. 2: Chemical structure of natural ester oil [5]

TABLE I TYPICAL CHEMICAL COMPOSITION OF NATURAL ESTERS

Vegetable oil	Saturated fatty acids [%]	Unsaturated Fatty Acids [%]		
		Mono	Di-	Tri-
Canola	7.9	55.9	22.1	11.1
Corn	12.7	24.2	58	0.7
Cottonseed	25.8	17.8	51.8	0.2
Peanut	13.6	17.8	51.8	0.2
Olive	13.2	73.3	7.9	0.6
soybean	14.2	22.5	51	6.8
Sunflower	10.5	19.6	65.7	-
High oleic sunflower	9.2	80.8	8.4	0.2

II. DGA DIAGNOSTIC TECHNIQUES

The ultimate objective of DGA is to identify the type of incipient fault inside a power transformer based on the dissolved gases. The identification of the incipient fault is done by using DGA diagnostic techniques. The diagnostic techniques identify the incipient fault by using either the key dissolved gas, gas ratios or graphical representation. The commonly used interpretation schemes are the IEC 60599 and Duval's triangle.

These diagnostic techniques are based on field data of in-service mineral oil-filled transformers whereby the dissolved gases are attributed to specific type of fault from visual inspection.

A. IEC 60599 ratios

The IEC 60599 diagnostic technique uses three gas ratios to deduce the incipient fault. The three ratios are C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 [4]. These three ratios are used to detect six categories of faults; partial discharge (corona type), low energy discharge, high energy discharge, low thermal faults, medium thermal faults and high thermal faults. These faults are detected according to Table II.

TABLE II IEC 60599 FAULT CATEGORIES

Fault type	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
Partial discharges (corona type)	Not significant	< 0.1	< 0.2
Low energy discharge	> 1	0.1-0.5	>1
High energy discharge	0.6 – 2.5	0.1 -1	>2
Thermal fault (T < 300 °C)	Not significant	>1	<1
Thermal fault (300 °C – 700 °C)	< 0.1	>1	1-4
Thermal fault (T > 700 °C)	< 0.2	>1	>4

B. Duval's triangle

The Duval's triangle diagnostic technique uses a triangular graphical representation of relative percentages of three gases (C_2H_4, CH_4 and C_2H_2) to identify the type of fault as shown in Fig. 3 [11]. The relative percentages of the three gases is deduced using equation 1-3 respectively.

$$\% CH_4 = \frac{CH_4}{CH_4 + C_2H_2 + C_2H_4} \times 100 \quad (1)$$

$$\% C_2H_2 = \frac{C_2H_2}{CH_4 + C_2H_2 + C_2H_4} \times 100 \quad (2)$$

$$\% C_2H_4 = \frac{C_2H_4}{CH_4 + C_2H_2 + C_2H_4} \times 100 \quad (3)$$

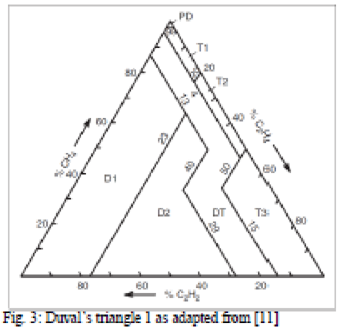

Fig. 3: Duval's triangle 1 as adapted from [11]

C. IEEE key gas

The IEEE key gas diagnostic technique identifies incipient fault based on the dominating dissolved gas. There are four categories of faults detected by this technique as shown in Table III [12].

TABLE III. IEEE KEY GAS FAULT CATEGORIES

Fault type	Key gas
Partial discharge or low energy sparking	Hydrogen
Arcing	acetylene
Oil overheating	ethylene
Cellulose overheating	Carbon monoxide

III. EXPERIMENTAL METHODOLOGY

The DGA of canola-based ester oil under creepage discharges is studied by simulating creepage discharges on the pressboard-oil interface and studying the corresponding dissolved gases.

A canola-based natural ester oil manufactured by M&I Materials was used in this work. The basic physical, chemical and electrical properties of the investigated ester oil are given in Table IV.

TABLE IV. IEEE KEY GAS FAULT IDENTIFICATION

Properties	Value
Appearance	Bright and clear
Density at 20 °C [kg/cm^3]	0.92
Viscosity at 40 °C [mm^2/s]	37
Flash point [°C]	260
Fire point [°C]	350
Pour point [°C]	-31
Dielectric breakdown @ 2.5 mm gap [kV]	75
Power factor @ 25 °C [%]	<0.2
Dissipation factor @ 90 °C	<0.03
Corrosive Sulphur	Non-corrosive
Water content [mg/kg]	50
Acid number	$\leq$ 0.04

A common method used for creating creepage discharges on the oil-pressboard interface is using the needle-plane electrode configuration with the pressboard placed between the electrodes; this configuration is based on applying high voltage on the point electrode and connecting the plane electrode to ground [2,13-15]. The high voltage applied on the needle electrode generates electrical discharges around the tip of the needle that results in tracking patterns on the pressboard surface. The direct application of high voltage on the surface of the pressboard through the needle creates an intense field which could result in electrical failure and puncture of the pressboard, hence a method for applying the high voltage at an acute angle is normally employed. The application of the high voltage at an acute angle ensures that the charges on tip of the needle electrode are directed to the surface of the pressboard rather than the bulk of the pressboard, this is done by creating a strong tangential component of the field on the pressboard surface and minimizing the vertical component of the field [2, 16-17].

The pressboard was preprocessed prior to the experiments by drying it and impregnating it with insulating oil under vacuum to remove moisture and gases. The needle electrode is made of steel and it has a tip radius of 40 µm tip radius. The pressboard has dimensions of 90 × 90 mm and thickness of 3 mm.

The creepage discharges were initiated by applying AC voltage on the samples from 0 kV in steps of 2 kV until 28 kV. The 28 kV was calculated as the voltage that is above partial discharge inception voltage and below surface flashover voltage [14]. The creepage discharge activity was simulated and monitored using the circuit set up in Fig. 4 [14].

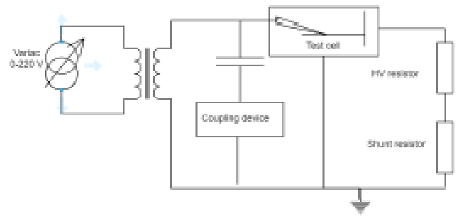

Fig. 4: Creepage discharge circuit set up

After the simulation of the creepage discharges, oil samples were taken at the bottom of the test cell using 50 ml glass syringes for the purpose of DGA analysis. The oil samples were sent to the chemical laboratory for gas extraction and analysis using gas chromatography.

A typical Phase Resolved Partial Discharge (PRPD) pattern of the simulated creepage discharges taken over 30 s of the natural ester and mineral oil is shown in Fig. 5 and Fig. 6 respectively. The PRPD pattern is similar to the one in [14].

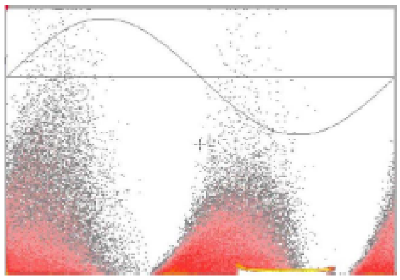

Fig. 5: PRPD pattern of canola based natural ester oil

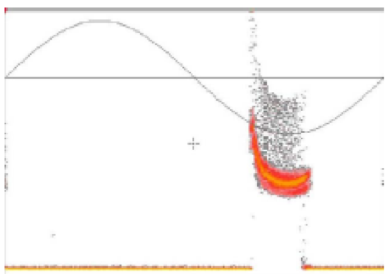

Fig. 6: PRPD pattern of mineral oil

IV. RESULTS AND ANALYSIS

A. Dissolved gases

The dissolved gases in mineral and canola-based ester oil that are generated from the creepage discharges are shown in Fig. 7. The results in Fig. 7 illustrates that canola-based ester oil and mineral oil generate similar type of dissolved gases under creepage discharges, these generated gases are; Hydrogen, methane, carbon monoxide, carbon dioxide, ethylene, acetylene and ethane. This finding is similar to the findings of Wang et al [13]. The similarity in the types of dissolved gases is attributed to the fact that both oils contain carbon-hydrogen and carbon-carbon bonds in their chemical structures hence similar gas generation mechanism occur in mineral and ester oil [18]. When a fault occurs, thermal energy from the fault breaks the carbon-hydrogen and carbon-carbon bonds into CH_3, CH_2, CH, C and H radicals. These radicals subsequently recombine with each other to form Hydrogen (H-H), methane (CH_3-H), ethane (CH_3-CH_3). Further decomposition forms ethylene (CH_2-CH_2) and acetylene (CH ≡ CH) [19].

The canola-based ester oil produced 35 % more hydrogen than the mineral oil and the total dissolved gases produced in the ester oil is 70% more than mineral oil. This high quantity of dissolved gases in canola-based ester oil than mineral oil is attributed to the high creepage discharge activity occurring in the ester oil than mineral oil which is demonstrated by the PRPD patterns in Fig.5 and Fig. 6. High creepage discharge activity occurs in ester oil due to the higher viscosity of ester oils compared to mineral oil [20]. The high viscosity of ester oil is a results of the hydrolysis process that occurs in ester liquids due to the presence of the fatty acid molecules. During hydrolysis, cross-linking reactions occur in the oil resulting in increased viscosity as shown by Fig. 8 [21]. The high viscosity of ester oil makes any gas bubbles to remain longer in the oil and subsequently initiate local discharges in the oil [14].

The difference in the quantity of the dissolved gases in the canola-based natural ester and mineral oil requires verifying if the DGA diagnostic techniques can be used for canola oil-filled transformers.

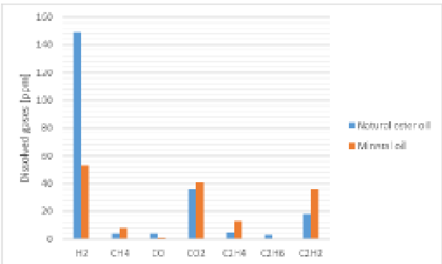

Fig. 7: Dissolved gases dissolved in canola-based ester oil and mineral oil

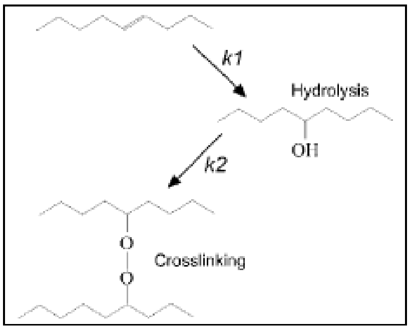

Fig 8: Hydrolysis process of ester liquids as adapted in [22]

B. Diagnostic techniques

According to the IEC 60599 standard, the simulated creepage discharge fault of this work is categorised as a low energy discharge fault [4]. The results of the IEC 65099 diagnostic technique in Table IV illustrate that this diagnostic technique cannot be used for the canola-based ester under creepage discharge since the CH_4/H_2 ratio is below the required boundary of 0.1-0.5 while the C_2H_2/C_2H_4 and C_2H_4/C_2H_6 ratios are within the boundaries of the low energy discharge fault. This implies that the IEC 60599 techniques requires modification for it to be used in canola oil filled transformers.

The Duval's triangle fault classification also categories the creepage discharge simulated in this work as a low energy discharge. The results of the fault diagnosis are shown in Fig. 9. The results demonstrate that Duval's triangle 1 can be used to correctly diagnose creepage discharges in the canola oil without modifying the boundaries of the triangle.

The IEEE key gas method classifies the simulated creepage discharge as a partial discharge/low energy sparking. According to this diagnostic technique, the dominating dissolved gas in the mineral and canola ester oil is hydrogen which correspond to the fault classification of partial discharge/low energy sparking. This implies that the technique correctly identifies the fault in both the mineral and ester oil, hence this technique can be used for canola oil filled transformers.

TABLE V. IEC 60599 FAULT DIAGNOSIS

Fault type	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Diagnostic result
Mineral oil	2.7	0.15	13	Low energy discharge
Canola-based ester oil	3.6	0.02	1.6	n/a

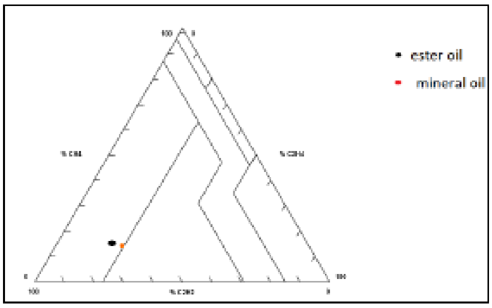

Fig.9: Duval's triangle 1 diagnostic results

TABLE VI. IEEE KEY GAS FAULT DIAGNOSIS

Fault type	H_2	CH_4	C_2H_4	C_2H_6	CO_2	C_2H_2	CO	Diagnostic result
Mineral oil	53	8	13	1	41	36	1	Partial discharge
Canola-based ester oil	149	4	5	3	36	18	4	Partial discharge

C. *Deterioration of pressboard*

The deterioration of pressboard is known to generate carbon and carbon dioxides in the insulation oil. According to IEC 60599, a ratio of CO_2/CO less than 3 is indicative of pressboard deterioration and a ratio greater than 10 is indicative of overheating of the pressboard [14]. The CO_2/CO ratio of canola-based ester oil and mineral oil was found to be 9 and 41 respectively which implies that the pressboard experienced mild overheating during the creepage discharge hence the low dissolved carbon monoxide.

V. CONCLUSION

The dissolved gases in canola-based natural ester oil under creepgae discharges has been investigted. The findings reveal that although canola-based ester oil has a different chemical structure than mineral oil, the generated gases under the simulated creepage discharges are similar in composition and differ in quantity. The quantity of dissolved gases in the natural ester oil is higher compared to mineral oil. This behaviour is attributed to the high creepage discharge activity in the canola oil. The evaluation of the ability of DGA diagnostic techniques to correctly identify the creepage discharge fault in the canola oil illlustrate that the Duval's triangle and IEEE key gas method can correctly identify the fault while the IEC 60599 ratios fail to identify the fault hence modification is required for using the technique in canola oil filled transformers.

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