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DISSOLVED GAS ANALYSIS OF TRANSFORMER FAULTS IN BIO-DEGRADABLE INSULATION OIL

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ABSTRACT
Existing dissolved gas analysis techniques were developed for mineral oil insulation used in power and distribution transformers. This paper presents results of experimental tests performed on laboratory models of transformer windings insulated with bio-degradable oil without involving cellulosic material. The dissolved gas analysis investigations were carried out and aimed at determining the potential use of existing DGA techniques and analysis to this new type of insulating liquid. To this end, vegetable oil and mineral oil samples were subjected to a number of fault conditions typical of those occur in transformers. They included partial discharge activity, arcing and overheating. For each type of fault, the gases produced were analyzed and compared.

KEY WORDS
Bio-degradable oil, mineral oil, partial discharge, overheating, dissolved gas analysis (DGA), hydro-carbon gases, transformer insulation.

1. Introduction

Insulating oil is very important for the heat dissipation and insulation of a liquid-filled transformer. Petroleum-based mineral oils purified to transformer grade oil are the commonly used insulating oil in transformers for more than a century. They are easy to produce, inexpensive, and have excellent dielectric and cooling behaviour. However, mineral oil has its disadvantages relating to environmental issues. It is poorly bio-degradable, thus will cause contamination to the soil and waterways if serious spills occur due to leakage and equipment failures. The other problem is the disposal of the mineral oils. Obviously, petroleum products are not conserved and will run out in the near future. Thus, biodegradable oils such as vegetable oils have been considered by the power utilities as the possible insulating liquids to replace mineral oils. Vegetable oils are natural products that are available in plenty. They have been used widely for edible purposes and lots of researches have been done on producing vegetable oils for insulating and cooling purposes. Vegetable oils are relatively more friendly to the environment as compared to mineral oils.

In this work, experiments were performed on laboratory models of transformer windings insulated with bio-degradable oil and mineral oil. Investigation was done on hydro-carbon gases produced by three types of transformer faults: partial discharge (PD), arcing and overheating. The laboratory partial discharge and arcing tests were performed in small chambers using mineral and vegetable oil without the presence of cellulosic materials (i.e. paper or pressboard). The overheating test was performed by heating the oils in the oven. Partial discharge activity was monitored using a commercial digital discharge detector and standard phase resolved analysis applied. At the end of each test, an oil sample was extracted and sent to a chemical laboratory of a local distribution utility for gas extraction and moisture measurement. The results of these investigations are presented in this paper and discussed with the aim of determining the efficacy of applying existing dissolved gas analysis methods for transformers insulated with bio-degradable oil.

2. Experiment Setup and Procedure

For referencing, the two bio-degradable oil types used in the tests are labeled A and B, and the mineral oil is labeled C. Table 1 lists the relevant properties of the three oils tested. Figure 1 shows the test cell which uses a point-plane electrode configuration. This configuration was used in testing PD and arcing faults.

Table 1: Relevant properties of tested oils

Properties	Standard	A	B	C
Dielectric Breakdown Voltage (kV)	ASTM D877	50-55		≥30
1mm gap	ASTM D1816	28-33		≥20
2mm gap		60-70		≥35
2.5mm gap	IEC60156		≥86	
Water Content (mg/kg)	ASTM D1533/IEC60814	20-30	≤50	≤35
Dielectric dissipation factor(%)	ASTM D924/IEC60247			
25°C		0.02-0.06	≤0.00379	≤0.05
100°C		1-3		≤0.30
Pour Point (°C)	ASTM D97	-18→-21	≤-18	≤-40
Flash Point (°C)	ASTM D92	323-330	≥225.1	≥145
Fire Point (°C)	ASTM D92	355-360		

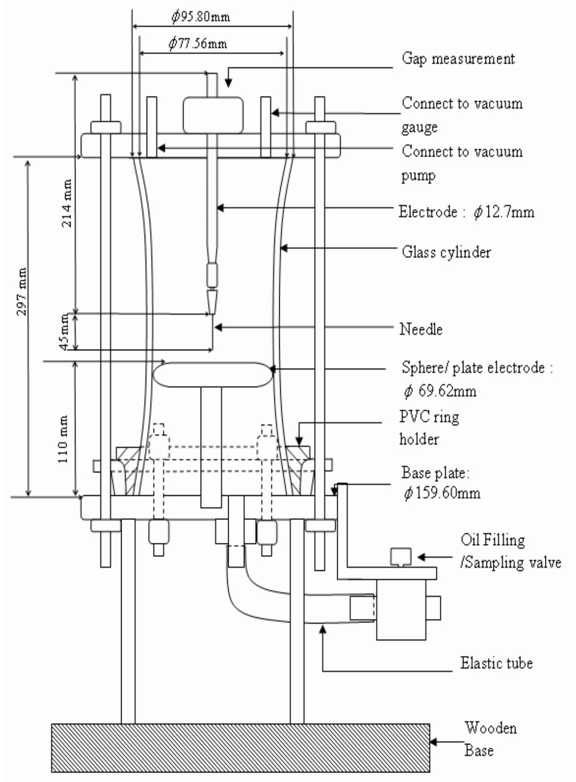


Figure 1: Point to plane electrode for PD and arcing test

2.1 Partial Discharge Test

Partial discharge activity of the bulk oil samples was achieved by application of test voltage above the PD inception level. The inception voltage levels depend on the electrode gap and dielectric strength of the oil. Previous investigations in this laboratory [1] have found that the test voltage adequate to generate PD activity in mineral oil is 23kV for a 20 mm gap, 16kV for 10mm and 4kV for 1mm. These values are above the partial discharge inception voltage and will generate significant PD activity. In order to make appropriate comparison between the oils, all three oils were tested under the same electrical stress.

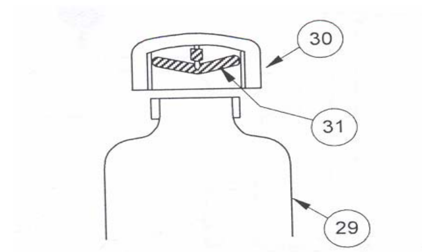
The voltage was increased from zero to the full test voltage in 1 kV steps every 10 seconds and then maintained at the full specified test voltage level for 600s. The PD activity was measured during that period. The test voltage was then reduced to zero and a rest time of 300s was allowed before the test was repeated. In all, the tests were repeated 5 times. The value used for PD magnitude determination was the arithmetic mean over the tests.

2.2 Arcing Test (Insulation Breakdown Test)

This test used the same configuration as the partial discharge test except that the voltage was increased until breakdown voltage as referred to in table 1. In this investigation, the breakdown was repeated for 200 times in each test before the oil sample was taken.

2.3 Overheating Test

The overheating test was performed by heating the oils in the oven at temperature between 130^{o}C to 140^{o}C. Special bottles with cap and ring that can withstand high temperature were used. These glass or metal bottles are capable of being sealed gas tight. They have screwed plastic caps holding a conical polyethylene seal as shown in Figure 2. A bottle and seal design is acceptable if it permits losses of hydrogen of less than 25% each week. In this investigation, the bottle was filled half full with oil and argon gas was added to fill the empty space. The oil was heated for more than 72 hours.

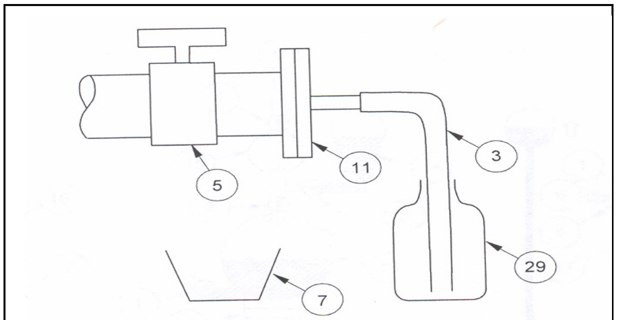


Key

29	Bottle
30	Hard plastic screw
31	Conical soft polyethylene seal

Figure 2: Bottle used for oil heating test

2.4 Oil Sampling Using Bottle



Key

3	Rubber connecting tubing
5	Equipment sampling valve
7	Waste vessel
11	Blank flange

Figure 3: Apparatus for sampling by bottle

It is important to take a sample that is representative of the bulk oil for obtaining a reliable diagnosis of the equipment. Even the most sophisticated extraction or diagnosis methods cannot overcome faulty samples. When sampling the oil, every precaution should be taken to deal with any sudden release of oil and avoid oil spillage. In this work, the International Standard for sampling oil for analysis of dissolved gas was followed. The standard applied is IEC 60567: Oil-filled electrical equipment - Sampling of gases and of oil for analysis of free and dissolved gases [2]. There are three different methods for sampling oil from the oil-filled equipment: by using syringe, sampling tube or bottle. In this work, the third method was used. As referred to figure 3 above, below are the steps to sample the oil:

i. The blank flange or cover (11) of the equipment-sampling valve is removed and the outlet cleaned with a lint-free cloth to remove all visible dirt.

ii. Connect the oil-proof plastic or rubber tubing (3) to the equipment.

iii. The sampling valve (5) is carefully opened and about 1 to 2 litres of oil allowed to flow to the waste (7) through the tubing (3) ensuring that all gas bubbles are eliminated before the oil sample is collected.

iv. Place the end of the tubing (3), with the oil still flowing, at the bottom of the sampling bottle and allow the bottle to fill slowly.

v. Allow about one bottle volume to overflow to waste, and then withdraw the tubing (3) slowly with the oil still flowing.

vi. Close the sampling valve (5) and disconnect the tubing.

vii. Tilt the bottle to allow the oil level to fall few millimeters from the rim so as to leave a small expansion volume. Place the bottle cap securely in position and label the sample.

2.5 Dissolved Gas Analysis

DGA detects fault gases generated by abnormal electrical and/or thermal operation in transformers. The main gases considered are H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO and CO_2. The relative quantities of these gases can be correlated with the fault type and the rate of gas generation can indicate the severity of the fault.

In this work, for the analysis purpose the tested oils were sampled using 200ml bottles for DGA test and 20ml for moisture test. All the samples were sent to a chemical laboratory of a local power utility for gas extraction and moisture measurement.

2.6 Dissolved Gas Analysis Interpretation

Existing standards such as IEEE standards and IEC standards provide several methods for evaluation of possible fault types based on fault gases generated. Common methods used for evaluation are the Key Gases method, Rogers Ratio method, IEC method, Nomograph method, Duval Triangle method, and Doernenburg Ratio method. These interpretation methods can be classified into two categories: methods that use gas ratios and methods that use direct values of fault gases to indicate type of faults.

An example of the first category is Roger's Ratio method. The diagnosis of faults is accomplished via a simple coding scheme based on ranges of the ratios. Tables 2 and 3 below are example of codes used by the Roger's Ratio method [4].

Table 2: Gas Ratio Codes

Gas Ratios	Ratio Codes
CH_4/H_2	i
C_2H_6/CH_4	j
C_2H_4/C_2H_6	k
C_2H_2/C_2H_4	l

Table 3: Roger's Ratio Codes

Ratio Code	Range	Code
i	<=0.1	5
	>0.1,<1.0	0
	>=1.0,<3.0	1
	>=3.0	2
j	<1.0	0
	>=1.0	1
k	<1.0	0
	>=1.0,<3.0	1
	>=3.0	2
l	<0.5	0
	>=0.5,<3.0	1
	>=3.0	2

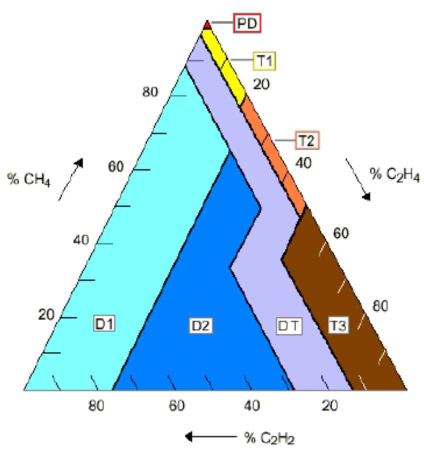
According to this method, the transformer is considered to have a fault if the diagnosis codes are as given in Table 4.

Table 4: Roger Ratio code sequence for fault

i	j	k	l	Diagnosis
0	0	0	0	Normal deterioration
5	0	0	0	Partial discharge
1-2	0	0	0	Slight overheating <150^{0} C
1-2	1	0	0	Overheating 150^{0} C-200^{0} C
0	1	0	0	Overheating 200^{0} C-300^{0} C
0	0	1	0	General conductor overheating
1	0	1	0	Winding circulating currents
1	0	2	0	Core and tank circulating currents, overheated joints
0	0	0	1	Flashover without power follow through
0	0	1-2	1-2	Arc with power follow through
0	0	2	2	Continuous sparking to floating potential
5	0	0	1-2	Partial discharge with tracking (note CO)

The Duval Triangle method is an example of the method that directly uses the amount of gas in it interpretation. The diagnosis was obtained by calculating the total accumulated amount of the three gases (CH_4, C_2H_2, C_2H_4) and dividing each gas by the total to find the percentage of each gas with respect to the total. The percentages of the total are then plotted on the triangle (Figure 4) to arrive at the diagnosis [8]. According to this method, the transformer is considered to have partial discharge when percentage of $CH_4 > 99\%$, C_2H_2 and $C_2H_4 < 1\%$.

With some interpretation methods, the value of the fault gases at first must exceed a threshold value L1 to ascertain whether there is really a problem with the unit and then whether there is sufficient generation of each gas for the ratio analysis to be applicable. Tables 5 and 6 show the values of L1 used. For other methods that do not depend on specific gas concentrations to exist in the transformer for the diagnosis, the normal limit of the individual gases must be exceeded to be valid. The L1 gas values for the Duval Triangle method are lower than those specified in the Doernenburg and Nomograph method. In this paper, the L1 values for the Duval triangle method are chosen as the reference limit.



Legend

PD = Partial Discharge
T1 = Thermal Fault Less than 300 °C
T2 = Thermal Fault Between 300 °C and 700 °C
T3 = Thermal Fault Greater than 700 °C
D1 = Low Energy Discharge (Sparking)
D2 = High Energy Discharge (Arcing)
DT = Mix of Thermal and Electrical Faults

Figure 4: Duval Triangle Diagnosis.[4]

Table 5: ***L1* for Doernenburg Ratio method and Nomograph method[5]**

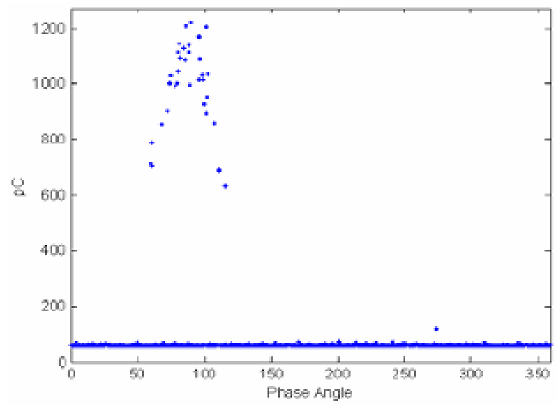
Key Gas	Concentrations *L1* (ppm)
Hydrogen (H_2)	100
Methane (CH_4)	120
Carbon Monoxide (CO)	350
Acetylene (C_2H_2)	35
Ethylene (C_2H_4)	50
Ethane (C_2H_6)	65

Table 6: ***L1* for Duval Triangle method [6]**

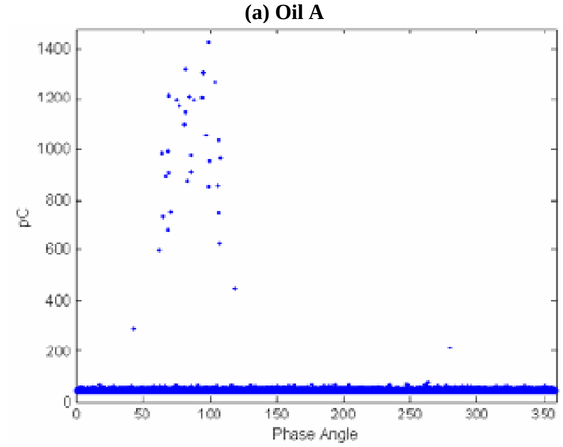
Gas	L1 Limit
H_2	100
CH_4	75
C_2H_2	3
C_2H_4	75
C_2H_6	75
CO	700
CO_2	7000

3. Results

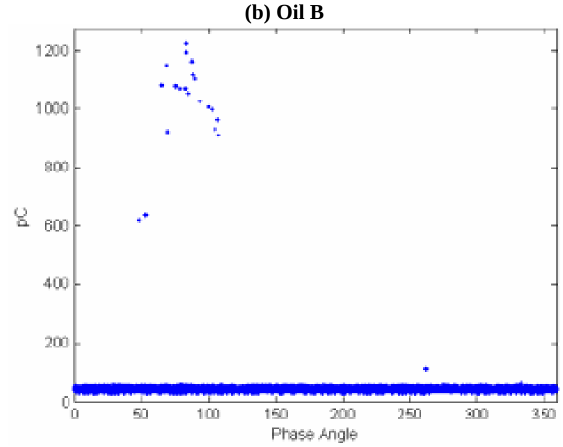
3.1 Partial Discharge Test



(a) Oil A



(b) Oil B



(c) Oil C

Figure 5: PD patterns recorded during the test

The discharge activity is monitored and recorded by using a digital (computer-based) discharge detector. The voltage at which the apparent charge of the discharge is equal to or larger than 100 pC is recorded. The captured discharge data was converted into ASCII format and MATLAB programming was used to process and analyze the recorded data. The average of the mean values of the two series is taken as the result. Figure 5 above shows the PD phase-resolved patterns.

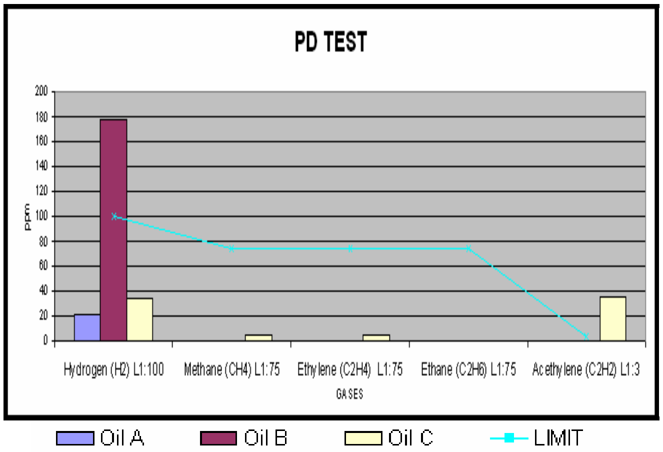


Figure 6: DGA result for PD test

The primary DGA result of the PD test is summarised in the bar chart shown in Figure 6. It clearly shows that for bio-degradable oil, only hydrogen (H_2) gas was produced during PD activity whereas for mineral oil, almost all the gases were produced by PD activity. Bio-degradable oil type B has a much higher level of hydrogen compared to the mineral oil and bio-degradable oil type A. This is consistent with its higher level of PD activity as referred to in figure 5. For mineral oil, the acetylene gas level exceeds the limit L1. Those gas values that exceed the L1 limits indicate faults when DGA interpretation method is applied. Table 7 shows the DGA interpretation results.

Table 7: DGA Interpretation for PD Test

Oil type	DGA Interpretation
Oil A	Normal
Oil B	Discharge with low energy
Oil C	Discharge with low energy

3.2 Arcing or Breakdown Test

The bar chart in Figure 7 summarised the result for hydro-carbon gases produced from the breakdown test. The chart shows that all oils tested produced all 5 types of hydro-carbon gases with hydrogen and acetylene levels exceed the L1 limits for all oils and also ethylene for oil B. The bio-degradable oils show higher value of hydrogen gas compared to that of mineral oil (>200ppm). Table 8 shows the DGA interpretation results.

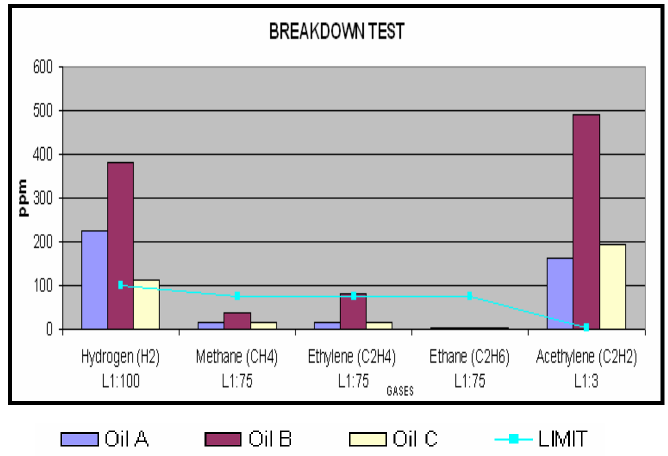
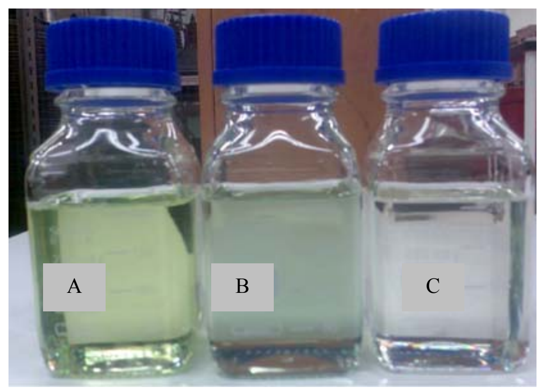


Figure 7: DGA result for breakdown test

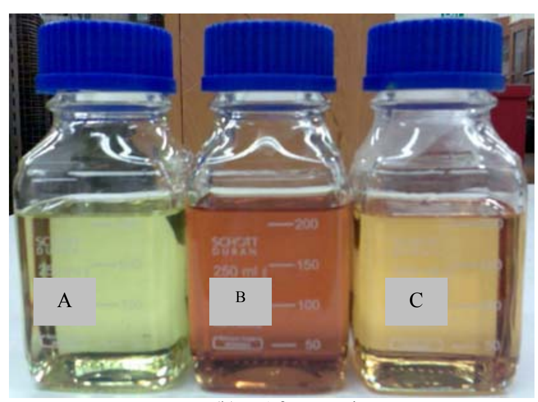
Table 8: DGA Interpretation for Arcing/Breakdown Test

Oil type	DGA Interpretation
Oil A	Discharge with low energy
Oil B	Discharge with low energy
Oil C	Discharge with low energy

3.3 Overheating



(a) Before heating



(b) After Heating

Figure 8: Oil condition before and after testing

All the oil samples were heated simultaneously at temperature between 130°C to 140°C. Figure 8 shows the change of oil color after being heated continuously for 4 days (96 hours).

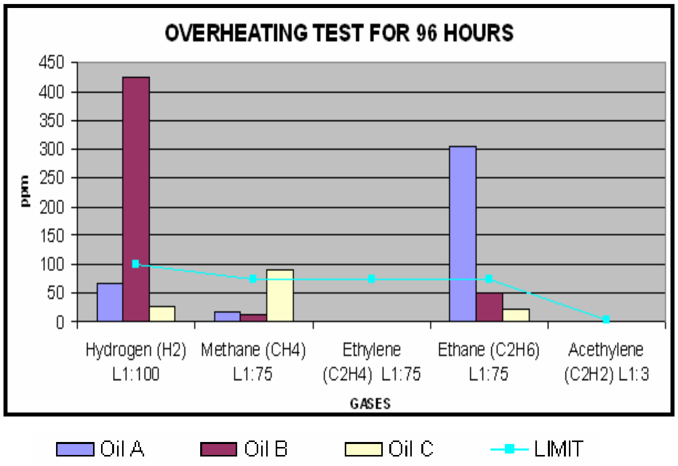


Figure 9: DGA result for overheating test

The DGA results obtained from the heating test are summarised in figure 9. They clearly show different trends of gases produced for each oil type. The gas type and the level of gases produced are different for each oil type. The highest gas produced is ethane for oil A, hydrogen for oil B, and methane for mineral oil. However, when applying the Duval Triangle method analyse the results, the interpretation gives the same type of fault indication (see Table 9).

Table 9: DGA Interpretation for Heating Test

Oil type	DGA Interpretation
Oil A	Thermal Faults Less Than 300^{o}C
Oil B	Thermal Faults Less Than 300^{o}C
Oil C	Thermal Faults Less Than 300^{o}C

4. Conclusion

Oil A and oil C are commercially available as transformer insulating oil whereas oil B is still in the development stage. The quantities and the trend of dissolved gases due to the faults in bio-degradable oil are quite different to those in mineral oil. Oil A was found to release only a limited number of gases during PD faults compared to the mineral oil. Thus, the prediction of PD faults based on existing DGA techniques for mineral oil is not applicable to bio-degradable oil. In overheating condition, even though the fault interpretation gives the same diagnosis it was found that mineral oil releases less amount of gases compared with bio-degradable oil and the highest type of gases produced is also different. Only in the breakdown test, the patterns of gases produced by both commercially used oils are similar. Here, hydrogen and acetylene exceed the normal limit and give the same DGA faults interpretation.

Based on these experiment results, it can be concluded that new DGA analysis and diagnosis methods for bio-degradable oil insulated transformers are required to enable correct recognition of transformer faults.

Acknowledgments

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