Dissolved Gas Analysis (DGA) of Partial Discharge Fault in Bio-degradable Transformer Insulation Oil

N.A. Muhamad, B.T. Phung, and T.R. Blackburn

***Abstract*-- Bio-degradable oil was commercially introduced as transformer insulation oil in 1999. Since then, the usage of this oil in the power industry has steadily increased and a lot of researches have been in progress to make bio-degradable oil as compatible as mineral oil. This paper presents results of experimental tests performed on laboratory models of transformer windings immersed in bio-degradable oil. The experiment involved an investigation of hydro-carbon gas products generated by partial discharge fault. The aim is to determine whether existing analysis techniques on partial discharge faults using DGA fault interpretation methods which were developed for mineral oil have to be modified when applied to insulation assessment of bio-degradable oil.**

***Index Terms*—Bio-degradable oil, mineral oil, partial discharge (PD), dissolved gas analysis**

I. Introduction

MINERAL Mineral oil-based dielectric fluids are widely used in power and distribution transformers worldwide. It is estimated that about 30 to 40 billion litres of mineral oil are in use in transformers operational worldwide [1]. However, mineral oil has a low relative permittivity, a low flash point, is slightly toxic and is a major environmental problem because of its poor (very slow) biodegradability. It will contaminate soil and waterways if spills occur [2]. For these reasons, alternatives to mineral oil for transformer use have been sought and bio-degradable oils such as vegetable oils have been developed for such use. Vegetable oils are natural products and are in plenty of supply. The most attractive features of vegetable oil-based fluids are that they are 95-100% bio-degradable, non-toxic and more environment friendly and thus pose little to no danger to aquatic or terrestrial, offshore or onshore environments. The bio-degradability of vegetable oil-based dielectric fluid can be maintained or improved further by purifying and adding environment friendly additives in formulating a vegetable oil based dielectric fluid [3].

Vegetable oils are slightly different in properties to mineral oils. The differences can be accommodated by relatively simple design modification. There are, however, some potential problems associated with the application of existing standard diagnostic techniques for the dielectric condition monitoring of transformer oil when this oil is used.

In this work, experimental tests were done using oils from three different sources: two are bio-degradable oils and the other is a mineral oil. The partial discharge fault simulation test was done to these oils in normal, dried and moisturized conditions. The effects of presence or absence of cellulosic materials (e.g. pressboard, paper) were also considered. The partial discharge experiment test and setup were done according to IEC 61294 [4] and IEC 60641-2 [5] standards. The oil sampling and gas extracting procedure were done according to the IEC 60567 [6] standard. At the end of each experiment, an oil sample was extracted and sent to a chemical laboratory of a local distribution utility for gas extraction and moisture measurement. The gases produced were analyzed and compared. The results of these investigations will be presented and discussed with a view to determining the validity of applying existing dissolved gas analysis methods for transformers with mineral oil to the case of bio-degradable oil.

II. Experiment Setup and Procedure

The two bio-degradable oil types are labeled A and B, and the mineral oil is labeled C. Table 1 lists the relevant properties of the three oils tested. For the case of testing without the presence of pressboard, Fig. 1 shows the test cell which uses a point-plane electrode configuration. For the case of testing with the presence of pressboard, the same test cell was used, as shown in Fig. 2, but with a plane-plane electrode configuration and a pressboard sandwiched in between. Different electrode gap spacing and different pressboard

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thicknesses were tested.

TABLE I
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		

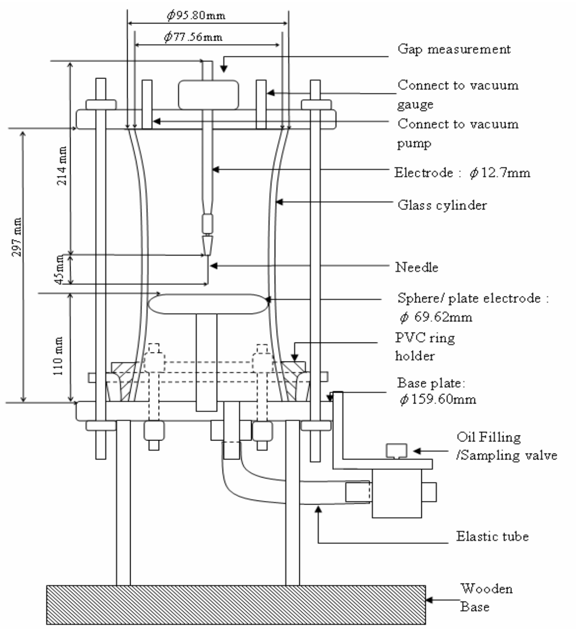


Fig. 1: Point to plane electrode (PD test without pressboard)

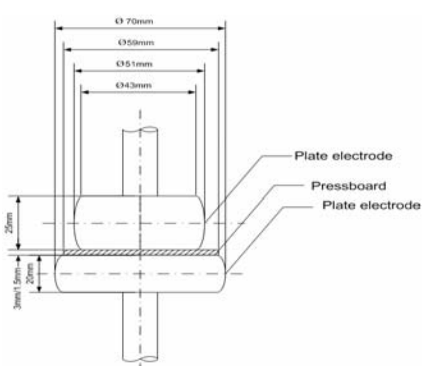


Figure 2: Plane to plane electrode (PD test with pressboard).

A. Drying and Moisturizing of the Test Oil

The test oil was dried in an oil dry-out plant for 48 hours. When required, moisture was added into the dried oil using measured quantities of water for specified quantities of oil. A 2 litre beaker was used to hold the dried test oil and a small 3ml syringe was used to inject demineralised water into the dried oil. A magnetic stirrer with hotplate was used for mixing water in the oil. The temperature was set to 50 ºC to avoid vaporization of water and the oil was stirred for 24 hours before being used for the test.

B. Drying and Oil Absorption of Pressboard

The procedure follows the IEC60641-2 Standard. The pressboard pieces were placed in an oven at a temperature of 105ºC for 48 hours. The test oil was placed in an aluminium tray and heated to 90ºC. The dried pressboards were then transferred to the test oil and left submerged. The pressboards were left in the oil for 6 hours without heating before testing.

C. Partial Discharge Test

The two main types of PD that commonly occur in transformers are corona-type partial discharge in bulk oil and surface (creepage) discharge [7]. In this experiment, corona-type partial discharges were generated using a point-plane (non-uniform field) electrode configuration and a piece of pressboard sandwiched between two flat electrodes (uniform field) was used to generate the surface discharges.

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 [8] have shown 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 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 and 10 times respectively for the bulk oil and pressboard tests. The value used for PD magnitude determination was the arithmetic mean over the tests.

D. 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.

In this work, for the analysis purpose the tested oil were sampled using 200ml bottles for DGA test and 20ml for moisture test. The procedure for sampling the oil is based on the IEC 60567 Standard: "Oil-filled electrical equipment - Sampling of gases and of oil for analysis of free and dissolved gases" [6]. All the samples were sent to a chemical laboratory of a local power utility for gas extraction and moisture measurement.

E. 2.5 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 used gas ratio 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. Table 2 and 3 below are example of codes used by the Roger's ratio method [9].

TABLE II
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 III
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 partial discharge fault if the diagnosis codes are as below:

TABLE IV
ROGER RATIO CODE SEQUENCE FOR PD FAULT

i	j	k	l	Diagnose
5	0	0	0	Partial discharge
5	0	0	1-2	Partial discharge with tracking CO

The Duval Triangle method is 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 (Fig. 3) 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%.

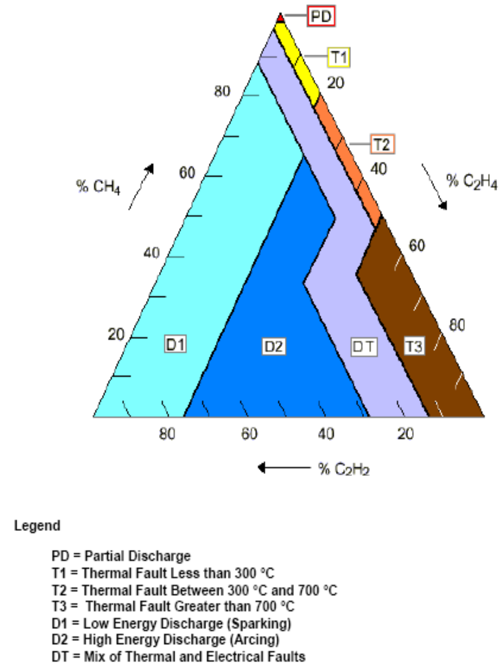


Fig.3: Duval Triangle Diagnosis.

In some interpretation methods, the value of the fault gases at first must exceed a threshold 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. Table 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.

TABLE V
L1 FOR DOERNENBURG RATIO METHOD AND NOMOGRAPH METHOD [10]

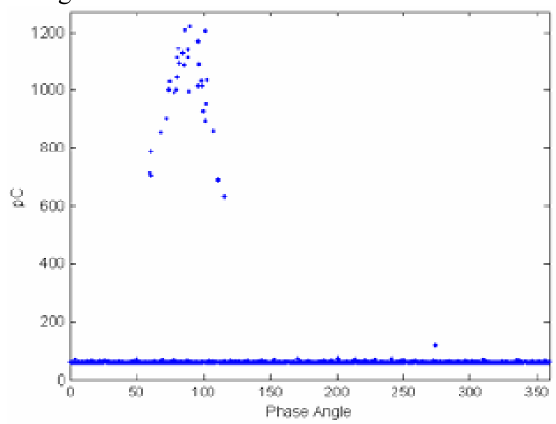
Key Gas	Concentrations *L1* (ppm)
Hydrogen (H_2)	100
Methane (CH_4)	120
Carbon Monoxide (CO)	350
Acetylene (C_2H_2)	35
Ethylene (C_2H_4)	50
Ethane (C_2H_6)	65

TABLE VI
L1 FOR DUVAL TRIANGLE METHOD [11]

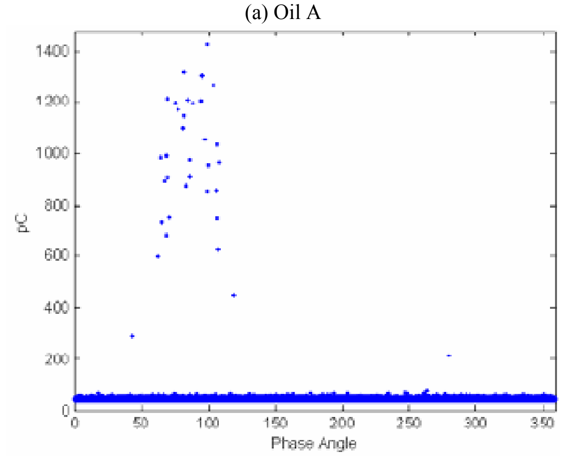
Gas	L1 Limit
H_2	100
CH_4	75
C_2H_2	3
C_2H_4	75
C_2H_6	75
CO	700
CO_2	7000

III. Analysis

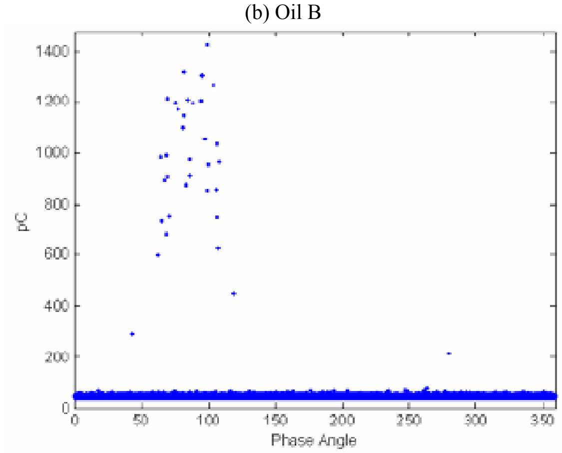
During the tests, the voltage is increased at a constant rate and the discharge activity is monitored and recorded by using a digital (computer-based) discharge detector. The voltage at which the apparent charge of the discharge is equal to or larger than 100 pC is recorded. A least 10 PDIV measurements are made on each of two different oil fillings of the cell. 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. Examples of the PD phase-resolved patterns plotted using MATLAB are shown in Fig 4.



(a) Oil A



(b) Oil B



(c) Oil C

Fig 4: PD patterns recorded for point to plane test using normal oil.

It can be seen that some of the L1 gas values for the Duval Triangle method are lower than those specified in the Doernenburg and Nomograph method. In this analysis, the L1 values of the Duval triangle are used as the reference limit.

IV. Results

A. Point to Plane PD Test

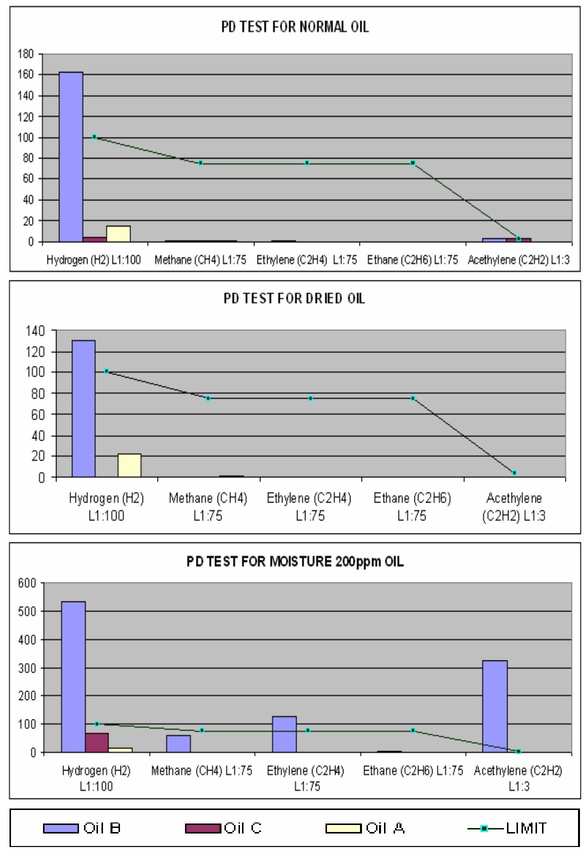


Figure 5: Bar charts of fault gases for PD tests without pressboard

Some of the preliminary results of the PD test without pressboard are summarized in the bar charts shown in Figure 5. The bio-degradable oils have a higher level of hydrogen (H2) compared to the mineral oil under dried and normal oil conditions. This is consistent with their higher levels of PD activity. Oil B has the highest hydrogen level (which is more than the L1 limit for the Duval Triangle[11]) under all conditions. When moisture was added into the oils, the level of H2 in the mineral oil became higher and was greater than that of oil A. It should be remembered that the actual moisture levels in mineral oil were lower than in the two bio-degradable oils. The level of H2, CH4, C2H4, and C2H2 in oil B increased with the addition of moisture. As a result of the increase in gas levels, three out of six of the fault gas components for the oil B exceeded Duval's L1 limit.

B. Plane to Plane PD Test

Fig. 6 shows the summary of selected initial results of the plane to plane tests. Results for PD test with pressboard show greatly different trends of fault gas composition of mineral oil for dried and moisturized oil (as compared to test without pressboard).

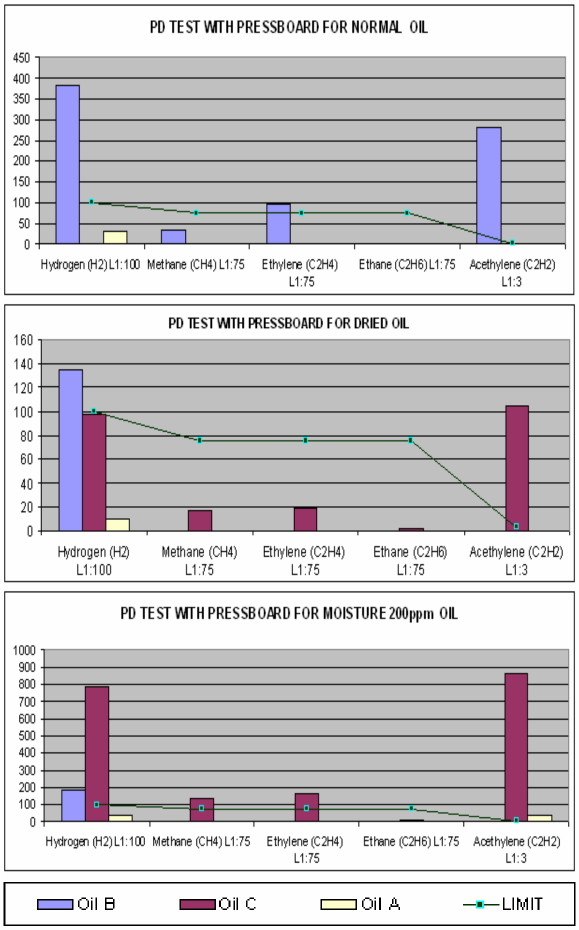


Fig. 6: Bar charts of fault gases for PD tests with pressboard

In the pressboard testing under dried and moisturized conditions, high levels of H2 and C2H2 are apparent with mineral oil. The amount of H2 and C2H2 are 100ppm more when compared to the point-plane testing. As for the amount of CH4 and C2H4, they are about 20ppm more. These gas quantities become larger and exceed the Duval L1 limit in high moisture conditions.

Among the three oils tested, biodegradable oil A is the one that has very few amounts of dissolved fault gases in both point-plane and plane-plane testing for all oil conditions. Only the PD test with pressboard for high moisture oil shows a higher level of C2H2 which is beyond the L1 limit.

V. Conclusion

Of the oils tested in this investigation, oil A and oil C are used commercially as transformer insulating oil. The other oil, oil B, is still in the development stage. From the experiment results, it can be concluded that new DGA analysis and diagnosis methods for bio-degradable oil insulated transformers are required to enable specification of transformer faults, at least for faults involving partial discharges. 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.

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