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Partial Discharge and Dissolved Gas Analysis In bio-degradable transformer oil

D. IMAMOVIC*, K.X. LAI, N.A. MUHAMAD, B.T. PHUNG and T.R. BLACKBURN#

The University of New South Wales
Australia

***Graz University of Technology**
Austria

SUMMARY

This paper presents results of experimental tests performed on bio-degradable oils for transformer application. The investigations covered two areas which are of importance given the increasing use of such oils. These are: (1) an investigation of partial discharge activity and characteristics in such oils and (2) an investigation of the standard hydrocarbon dissolved gas products produced by partial discharge activity. The fundamental aim of the investigations was to provide information as to whether the existing analysis techniques of PD pattern recognition and DGA ratio methods are valid when used for insulation assessment with bio-degradable transformer oil. Previous tests had indicated that the partial discharge and breakdown behaviour of vegetable oil is changed significantly by comparison to standard mineral oil when moisture is present in the oil.

For the purpose of comparison, the partial discharge tests were performed in small chambers using both mineral and vegetable oil, with and without moisture, over a range of temperature corresponding to typical operating levels in in-service transformers. Tests were performed both on oil only and on test models using electrically stressed pressboard discs to simulate the presence of impregnated paper in transformers. Partial discharge activity was monitored using both the standard IEC60270 phase resolved analysis method and non-standard time and frequency domain PD waveform methods.

The dissolved gas analysis investigations were aimed at determining the potential use of existing DGA techniques and analysis to this new type of insulating liquid in power and distribution transformers. To this end vegetable oil and mineral oil samples were subjected to PD fault conditions typical of those in transformers. There included partial discharge generation in both the oil and oil/pressboard models with and without moisture. The gases produced were analysed by standard GC methods.

The results of the investigation showed that there was some significant variation of both PD characteristics and dissolved gases in the oils after being subjected to PD activity. The PD magnitudes and patterns varied depending on the oil and the generation of the traditional DGA gases varied considerably between the oils and varied depending on the level of moisture present.

While the tests reported are of limited scope and are not extensive and detailed enough to allow general conclusions, the results indicate that the PD and DGA behaviour of bio-degradable oils may not able to analysed, in terms of fault identification, in the same way as has been used for mineral oils.

KEYWORDS: Bio-degradable oil; Partial Discharge; Dissolved Gas Analysis

Email: t.blackburn@unsw.edu.au

1. INTRODUCTION

Petroleum-based mineral oils purified to transformer grade have been used in transformers for more than a century. They have excellent dielectric and thermal dissipation characteristics. However, the use of mineral oil is a major environmental problem because of its poor (very slow) biodegradability. It will cause contamination to soil and waterways if spills occur. Thus, disposal of transformer oil is a problem. 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 readily bio-degradable and are thus more friendly to the environment than mineral oils.

Vegetable oils have electrical and thermal characteristics that are adequate for the dielectric and thermal requirements of transformer design [1,2]. While they 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 standard diagnostic techniques used for the dielectric condition monitoring of transformer oil. The most useful diagnostic techniques for current asset management of transformers are partial discharge detection and analysis and dissolved gas analysis. Both diagnostics have been developed in the last twenty years to a stage where it is possible to identify fault types from detailed analyses of the data produced. However the analysis is based heavily on the chemical composition and structure of the oil. This is particularly the case with the DGA method which requires ratio analysis of the various gaseous species produced by the faults on the oil. The most common mineral oil is a basic naphthenic structure while the vegetable oil is an olefin structure. The result is that the disintegration products of the two oil types under electrical discharge and thermal breakdown may be quite different in both product species and quantity. There is thus some uncertainty associated with the application of standard PD and DGA analysis techniques to vegetable oil. The investigations reported here were aimed at determining the basic characteristics of PD and DGA behaviour of transformer grade vegetable oil.

Experimental tests were performed on laboratory models of transformer windings insulated with bio-degradable oil and standard mineral oil. The investigations covered two main areas: (i) an investigation of partial discharge activity and breakdown tests and their characteristics and (ii) an investigation of hydrocarbon gas products generated by various fault types similar to those typically covered by existing dissolved gas analysis in mineral oil insulation.

The partial discharge and breakdown tests were performed in small test chambers using mineral and vegetable oil, with and without moisture, over a range of temperature corresponding to typical operating levels in in-service transformers. Tests were performed both with oil only in the chamber and also using oil-impregnated paper-covered copper conductors to simulate typical transformer winding configurations with electrical stresses typical of those in transformers.

Partial discharge activity was monitored using both standard phase resolved analysis methods and time and frequency domain waveform methods. The DGA investigations were aimed at determining the potential use of existing analysis to the new bio-degradable oils. To this end vegetable oil and mineral oil samples were subjected to a number of fault conditions typical of those that occurs in transformers. There included partial discharge activity, arcing and overheating in the laboratory models. The gases produced were analysed and compared for similar type faults as characterised in mineral oil.

2. TESTING OIL

2.1 Mineral Oil and Bio-degradable Oils

The mineral oil used was standard commercial Shell Diala MX. This product has oxidation inhibitor added to extend service life. It complies with IEC 60296-1982. Two bio-degradable oils were used. They were Envirotemp FR3, a commercial oil produced by Cooper Power Systems [3]. The other was BiolectricX, a bio-degradeable oil being developed by TACS, CSIRO and Curtin University in Australia. It is not yet commercially available. Envirotemp FR3 is formulated from vegetable oils and has various performance enhancing additives.

2.2 Comparison between the commercial oils

The relevant properties of the three oils tested are shown in Table 1 below.

Table 1: Relevant properties of Shell Diala MX, BiolectricX and Envirotemp FR3 [3]

		Shell Diala MX	Envirotemp FR3	BioelectriX
Dielectric Breakdown Voltage (kV)	ASTM D877	≥ 30	50-55	
1mm gap	ASTM D1816	≥ 20	28-33	
2mm gap		≥ 35	60-70	
2.5mm gap	IEC60156			≥ 86
Water Content (mg/kg)	ASTM D1533/IEC60814	≤ 35	20-30	≤ 50
Dielectric dissipation factor (%)	ASTM D924/IEC60247			
25 °C		≤ 0.05	0.02-0.06	≤ 0.00379
100 °C		≤ 0.30	1-3	
Pour Point (°C)	ASTM D97	≤ -40	-18→-21	≤ -18
Flash Point (°C)	ASTM D92	≥ 145	325-330	≥ 225.1
Fire Point (°C)	ASTM D92	-	355-360	-

3. ANALYSES

3.1 Partial Discharge

The two main types of PD that commonly occur in transformers are [4]:

- HV Corona-type partial discharge in bulk oil

In the tests reported here, corona-type partial discharges were generated in a point-plane, non-uniform field, electrode configuration.

- Surface (creepage) Discharge

In the laboratory tests, a piece of pressboard sandwiched between two flat electrodes (uniform field) was used to generate the surface discharges.

In both cases the main contaminant used was moisture.

3.2 Dissolved Gas Analysis (DGA)

DGA detects fault gases generated by abnormal electrical and/or thermal operation in transformers. The main gases used 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 type fault and the rate of gas generation can indicate the severity. There are several common methods developed to do the interpretation of the fault type from the dissolved gas data. The Duval Triangle method [5] was used for the analysis of the products.

4. TEST SETUP AND PROCEDURE

4.1 Point-plane Configuration

To produce Partial Discharges in insulating liquids under controlled conditions, it is appropriate to have an electrode arrangement with strongly inhomogeneous electrical field |1/r| >> 100. This achieved with a point (needle) – plane arrangement. Partial discharge activity of the bulk oil samples was obtained 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 [6] have shown that 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. To have an appropriate comparison between the investigated oils, all three oils were tested under the same electrical stress.

The voltage was increased from zero to full test voltage in 1 kV steps every 10 seconds and was 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.

The test cell used for the experiment was constructed according to IEC60897. The needle used had a radius of curvature of$1.2\mu m$. The flat plane electrode had a diameter of 70 mm. Three different spacings between the needle tip and the flat electrode were used: 1mm, 10mm and 20mm. The point-plane configuration together with the test cell is shown in Fig.1.

4.2 Pressboard Configuration

Determination of the PD magnitude with pressboard required higher voltages than the bulk oil tests. The PD inception voltages for the three oils with pressboard varied a little and so the tests for each oil were carried out under different electrical stress and the determination of the PD inception and extinction voltage method was used to characterise PD behaviour. The voltage was increased as described above and the same application and rest periods were used.

The same test cell was used as for the point-plane configuration. A HV plate electrode with 51mm diameter and an earthed plate electrode with 70mm diameter were used to sandwich a piece of pressboard. The diameter of the pressboard disc was 59mm with a thickness of either 1.5mm or 3mm. The pressboard configuration is shown in Fig.2.

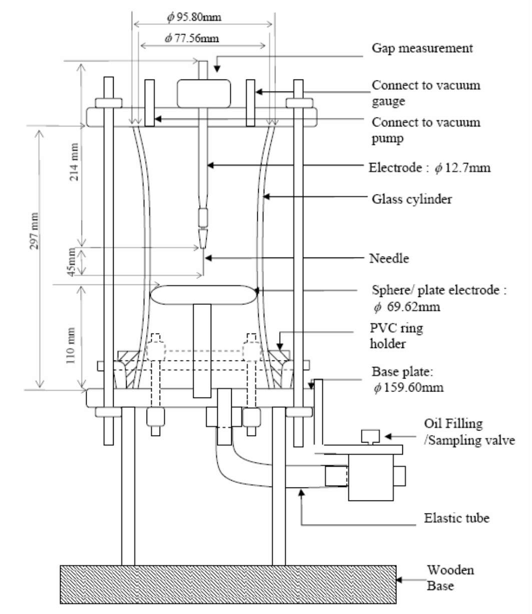

Fig.1 The test cell and the point-plane setup

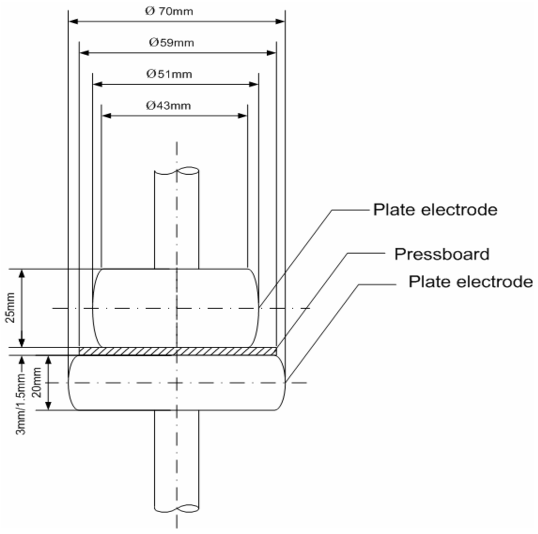

Fig.2 Pressboard Configuration

4.3 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 inserted into the dried oil using measured quantities of moisture for specified quantities of oil. A 2L beaker was used to hold the dried test oil and a small 3ml syringe with 0.4mm diameter needle was used to inject demineralised water into the dry test oil. A magnetic stirrer with hotplate was used to have the water completed mixed in the test oil. The temperature was set to 50 ºC to avoid vaporization of water and the test oil was stirred for 24 hours. Three different nominal moisturized levels: 20ppm, 100ppm and 200ppm were used.

4.4 Drying and Oil Absorption of Pressboard

This procedure follows the Standard IEC60641-2.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 90 ºC. 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.

4.5 Dissolved gas Analysis

After the partial discharge tests were completed the test oil samples were then removed carefully and sealed and sent for standard DGA testing in a gas chromatograph at the test laboratories of EnergyAustralia.

5. TEST RESULTS

5.1 Partial Discharge testing

5.1.1Phase Resolved Analysis

Tests were carried out under same electrical conditions but with different moisture content. Five diverse moisture content levels were tested. These are designated as (i) dried, (ii) normal (as delivered), (iii) 20ppm, (iv) 100ppm, (v) 200ppm. The last three levels are nominal only as subsequent moisture tests using the Karl Fischer method showed that the moisture addition procedure described did not result in those actual levels of moisture content. For mineral oil all attempts at adding moisture only achieved a constant level. Thus, except for "dried" mineral oil all other PD tests with mineral oil were performed with the same moisture content, so it is not surprising that the repetition rate as well as the PD magnitude of Diala MX are similar for all tests. The average PD magnitude for all tests is about 1200pC, whereas the PD magnitude for dried mineral oil is 900pC.

The phase resolved results for Envirotemp FR3 showed that this oil has comparable PD activity with the Diala MX; the PD magnitude is about 950pC for dried oil and increased up to 1450pC for "200ppm" moisture content. The repetition rate was constant over all tests and the patterns are analogous to Diala MX except for PD activity on the negative half-cycle with a magnitude of 200pC.

The BiolectricX oil had higher PD activity for all bulk oil tests. The average PD magnitude for "dried" oil is over 1000pC; for "normal (as delivered)" oil is 1450pC and rises over 1600pC for 200ppm moisture content. This oil was the most variable in terms of test results.

Typical phase resolved PD results are shown in Figures 3–14 for different conditions, with peak PD magnitudes given. The figures show the several examples under various conditions. Figs.3- Fig.5 show the PD results for the three different oils under "normal condition (as delivered) with the point-plane setup and 20mm gap. Fig.6- Fig.8 show the PD results for the different oils under moisture condition of "200ppm" with the point-plane setup of 20mm gap.

The phase resolved results for PD tests with pressboard of different thickness are different for all three oils. Although the mineral oil was not able to be properly moisturized, the results are very irregular in repetition rate as well as in the PD patterns. The average PD magnitude for "dried" Diala MX oil is 200pC at 19kV for tests with 1.5mm pressboard and over 350pC at 25kV for tests with 3mm pressboard. There is significant difference in PD activity for the tests with both thicknesses of pressboards. The repetition rate for 3mm is lower than for 1.5mm tests. The PDs occur in both positive and in negative half-cycle with the same maximum.

The Envirotemp FR3 showed very stable and constant PD magnitude and patterns for all tests. Even though the repletion rate is high, the PD maximum is considerably lower than for Diala MX. The PD magnitude for the tests with 1.5mm pressboard is constant over all moisture conditions and is under 90pC for "dried" oil and over 150pC for "200ppm" moisture conditions. The voltage used was 18kV and is similar to that of the tests with Diala MX. The results with 3mm and 1.5mm pressboard are similar in magnitude and repetition rate. The test voltage for 3mm was 29kV, compared to 25 kV for the mineral oil.

For the BiolectricX results for both tests it was difficult to produce PDs under controlled conditions. The PD magnitude for the tests with the 1.5mm pressboard range from 900pC for "dried" oil to over 1100pC for "200ppm" moisture content at a lower electrical stress (16 kV) than for the other oils. The same results were obtained from the tests with 3mm pressboard. The PD magnitude was 600pC for dried oil and over 850pC "200ppm" oil. The test voltage was 25kV.

Fig.9 - Fig.11 show the PD results for the three different oils under dried condition with 1.5mm thick pressboard. Fig.12 - Fig.14 show the PD results for the three different oils under moisture condition of "100ppm" with 3mm thick pressboard.

5.1.2 PD waveform in Time and Frequency Domains

For the point-plane configuration, Fig.15 shows the typical PD signals in the time and frequency domains for the point plane test. There were some differences in the rise times of the PDs in the oils. The rise times for Diala MX, Envirotemp FR3 and BioElectricX are about 4ns, 4ns and 12ns respectively. Fig.16 shows the typical frequency analysis results. The main frequencies of the PD signals for Diala MX, Environtemp FR3 and BioElectricX were 27MHz, 48MHz and 26MHz.

For the pressboard configuration, Fig.17 shows the typical PD signals in time domain for all the three types of oil. The rise times for Diala MX, Envirotemp FR3 and BiolectricX are approximately 10ns, 12ns and 10ns respectively. Fig.18 shows the typical frequency spectrum. The main frequencies of the PD signals for Diala MX, Environtemp FR3 and BiolectricX were 12MHz, 14MHz and 13MHz.
While there is a significant difference in the frequency spectrum between the three when only oil is involved in the PD generation, when interfaces with pressboard are present, the PD frequency spectra are much more similar, indicating that the pressboard involvement is the dominant feature.

Diala MX **Environtemp FR3** **BioElectricX**

Point-plane

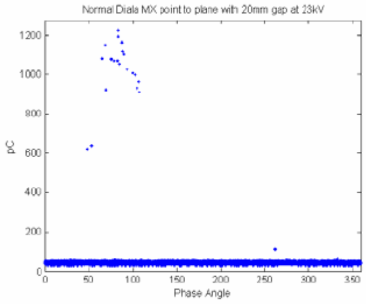

Fig.3 "Normal" condition with 20mm gap at 23kV
Peak PD = 1227pC

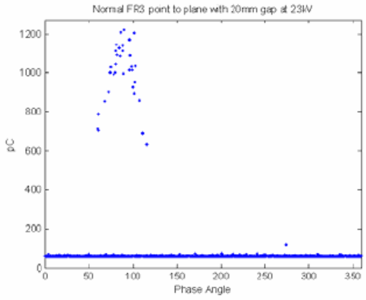

Fig.4 "Normal" condition with 20mm gap at 23kV
Peak PD = 1221pC

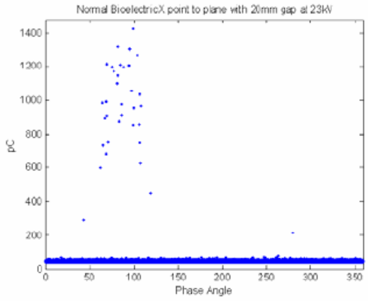

Fig.5 "Normal" condition with 20mm gap at 23kV
Peak PD = 1425pC

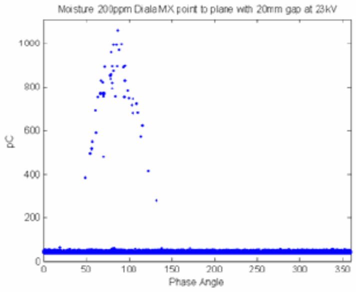

Fig.6 Moisture "200ppm" with 20mm gap at 23kV
Peak PD = 1060pC

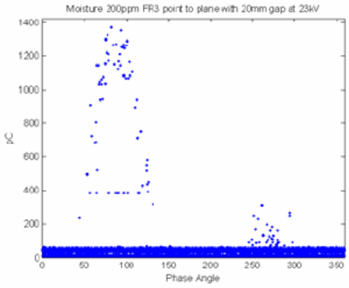

Fig.7 Moisture "200ppm" with 20mm gap at 23kV
Peak PD = 1372pC

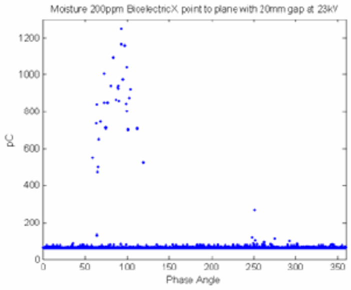

Fig.8 Moisture "200ppm" with 20mm gap at 23kV
Peak PD = 1251pC

Pressboard

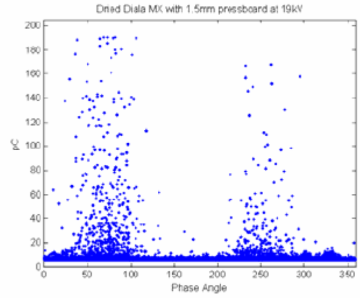

Fig.9 "Dried" condition with 1.5mm pressboard at 19kV (Peak PD = 190.3pC)

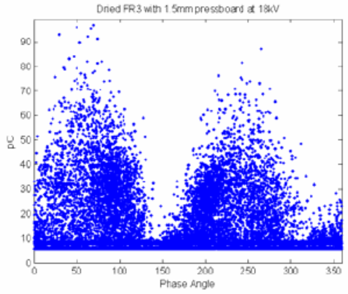

Fig.10 "Dried" condition with 1.5mm pressboard at 18kV (Peak PD = 99.23pC)

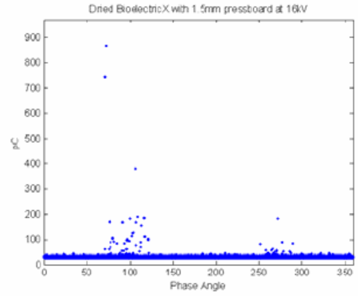

Fig.11 "Dried" condition with 1.5mm pressboard at 16kV (Peak PD = 971.1pC)

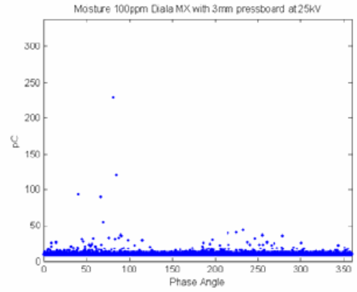

Fig.12 Moisture "100ppm" with 3mm pressboard at 25kV (Peak PD = 338.4pC)

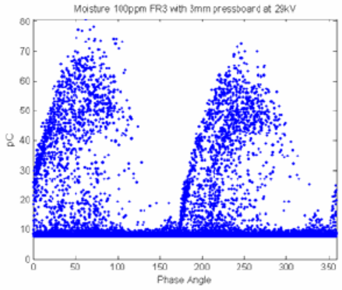

Fig.13 Moisture "100ppm" with 3mm pressboard at 29kV (Peak PD = 80.62pC)

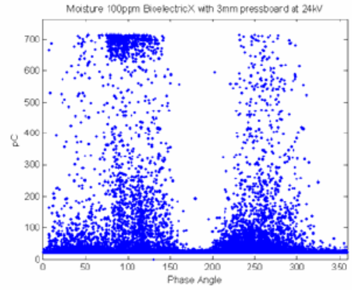

Fig. 14 Moisture "100ppm" with 3mm pressboard at 24kV (Peak PD = 715.4pC)

Point-plane configuration

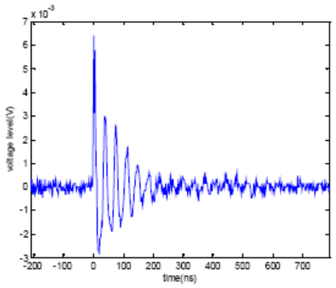

Fig.15 Typical PD signals in time domain

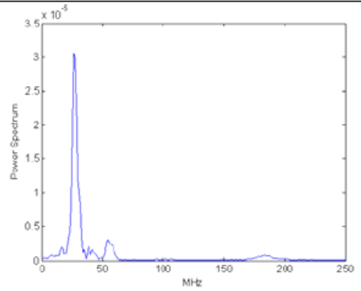

Fig.16 Typical power spectrum (frequency domain)

Pressboard configuration

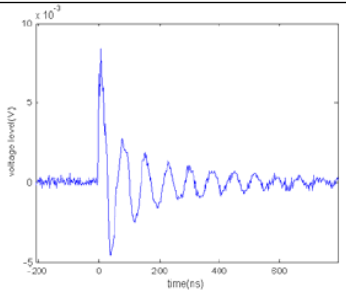

Fig.17 Typical PD signals in time domain

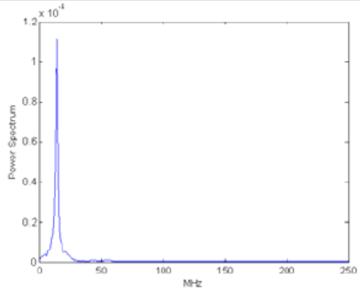

Fig.18 Typical power spectrum (frequency domain)

5.2 Dissolved Gas Analysis

After the PD testing, the oil samples were removed and extracted according to the IEC60567 standard. 200ml bottles were used for gas extraction and for moisture measurement. Fig.19 shows the DGA results obtained from the tests. The left side charts are the results with the point-plane configuration. Those on the right are the results with the pressboard configuration.

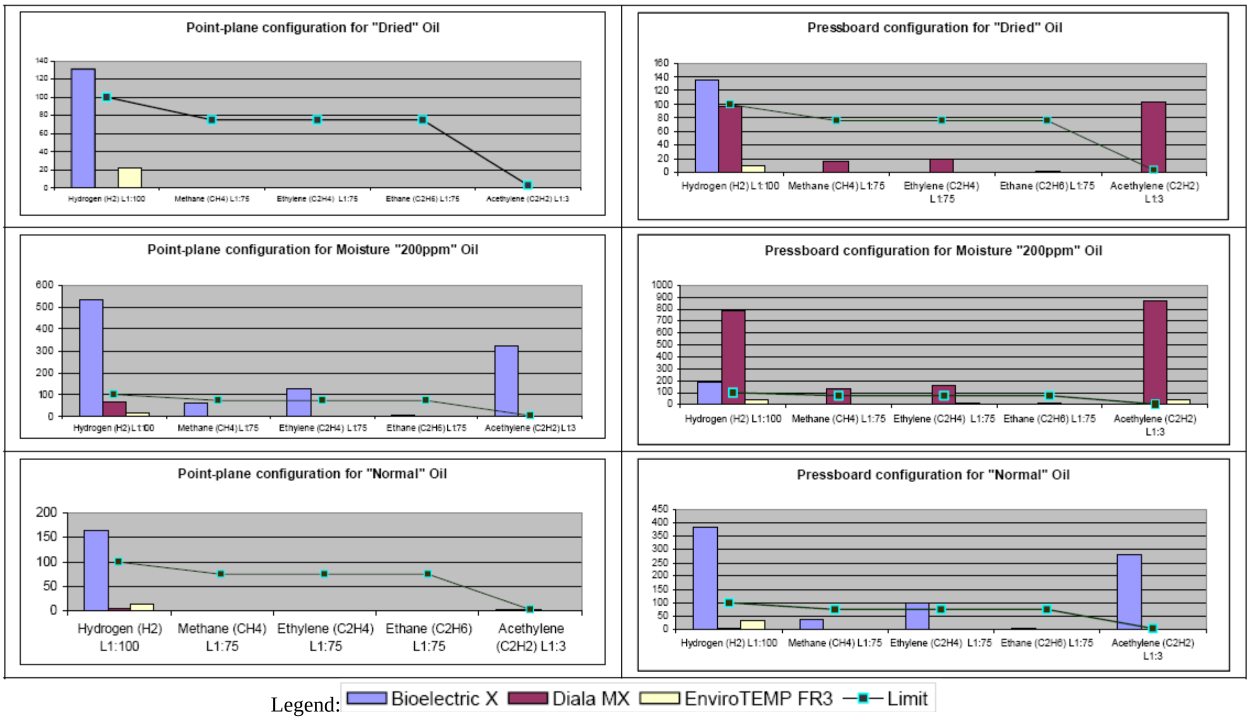

Fig. 19: Bar charts of faults gases component for PD test with and without pressboard

The bio-degradable oils have a higher level of hydrogen (H_2) compared to the mineral oil under dried and normal oil conditions. This is consistent with their higher levels of PD activity. BiolectricX has the highest hydrogen level (which is more than the L1 limit for the Duval Triangle) under all conditions. When moisture was added into the oils, the level of H_2 in the mineral oil became higher and was greater than that of Envirotemp FR3. It should be remembered that the actual moisture levels in mineral oil were lower than in the two bio-degradable oils. The level of H_2, CH_4, C_2H_4, and C_2H_2 in BioElectricX 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 BiolectricX exceeded Duval's L1 limit.

The results for the tests with pressboard configuration show great variations in the trend of fault gas composition for mineral oil under dried and moisturized conditions compared to the tests with point-plane configuration. In the pressboard testing under dried and moisturized conditions, high levels of H_2 and C_2H_2 are apparent with mineral oil. The amount of H_2 and C_2H_2 are 100ppm more when compared to the point-plane testing. As for the amount of CH_4 and C_2H_4, they are about 20ppm more. These gas quantities become larger and exceed the Duval L1 limit in high moisture conditions. Among the three types of oil, Envirotemp FR3 has low quantities of fault gases in both point-plane and pressboard testing under different conditions. Only the pressboard testing at high moisture levels in Envirotemp FR3 shows a higher amount of C_2H_2 : this is beyond the Duval L1 limit.

6. CONCLUSIONS

Of the oils used in this project, Envirotemp FR3 and Shell Diala MX are used commercially used as transformer insulating oil. The other oil, BioelectricX, is still in the development stage. From the results of the experiments, it can be concluded that new DGA analysis and diagnosis methods for bio-degradable oil insulated transformer are required to enable specification of specific transformer faults, at least involving PD activity. The quantities and the trend of dissolved gases during the faults in the bio-degradable oil are quite different to mineral oil. Envirotemp FR3 was found to release only a limited number of gases during PD faults compared to the mineral oil. Thus, the prediction of transformer PD faults based on current DGA techniques for mineral oil is not applicable to bio-degradable oil.

These investigations have shown that the partial discharge analysis and pattern recognition method can be used for assessment of bio-degradable oils. The results revealed that the commercial oil Envirotemp FR3 is quite appropriate for this aim, as the oil is very stable in patterns, in repetition rate as well as in PD magnitude. The outcomes are comparable with the mineral oil even though the influence of moisture has to be considered.

It is not possible to draw detailed conclusions on the basis of such limited testing however, and other faults such as low level PD, thermal faults and arcing need to be performed to enable a valid conclusion. However it is apparent that the application of existing methods of analysis will not necessarily give true indications of oil qualities for transformer assessment.

Acknowledgements

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