INSULATION CONDITION MONITORING OF AN ALTERNATIVE TRANSFORMER DIELECTRIC FLUID USING PDC MEASURMENT TECHNIQUE

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Abstract: Petroleum-based mineral oils have long been used in oil-filled power transformers. However, recent developments have led to the introduction of environmentally safer and more sustainable alternative dielectric fluids to the mineral oil. Among them is the Envirotemp FR3. It is a natural ester oil formulated from seed oils with excellent biodegradability characteristics and a relatively high flash point. This research aims to evaluate the conductivity of this alternative fluid based on polarisation and depolarisation currents (PDC) measurement. The experiments were conducted to establish the differences between the PDC patterns produced by both mineral oil (Shell Diala BX) and alternative oil (Envirotemp FR3). As the dielectric properties of insulating oil can be strongly influenced by moisture and temperature, the testing is performed at different levels of moisture and temperatures so that the dielectric response function and the conductivities of the oil samples can be found and compared. Each oil type was tested under the effect of 2 different levels of moisture ('dried' and 'normal') and 4 different levels of temperature ranging from 20°C to 80°C. The effect of moisture as well as the temperature on the polarisation and depolarisation currents and hence on the conductivity of both mineral and biodegradable oils is then discussed.

1 INTRODUCTION

A safe and economic operation of distribution networks is heavily dependent on reliability of power transformers, but unfortunately, the state of operating for a large number of transformers is unknown. Degradation of the insulation materials caused by thermal stress on the insulating oil and paper can considerably influence the transformer's life. Depending upon operating conditions, the conductivity of both oil and paper can significantly change during the transformer operation. Thermal stress causes degradation of oil and the cellulose paper. Consequently, the paper becomes brittle and the resistance against mechanical stress will decrease. Hence, the expected life of the transformer will eventually diminish. The temperature effect becomes more profound in an open substation environment, where the external environmental conditions are hard to be predicted and controlled. Therefore, the study of the temperature effects on dielectric behaviour of an oil/paper insulation system in a field transformer is essentially important.

Time domain polarisation and frequency domain spectroscopy (FDS) measurement are the techniques which have been used for condition monitoring of power transformer insulation. Return voltage measurement (RVM) and the polarisation and depolarisation current (PDC) are amongst the prominent dielectric response measurement techniques based on time domain measurement [1]. Due to the ability to evaluate the condition of oil and paper separately without opening the tank of the transformer, PDC measurement has achieved great popularity. Using this technique, the information about the oil conductivity can be provided short after the application of DC test voltage. The PDC patterns of transformer insulation such as mineral oil have been previously studied by many researchers. But the investigations do not cover a PDC analysis for biodegradable oil in a wide range of temperature. In this paper, PDC was conducted merely on mineral and biodegradable oil samples at different temperatures.

2 PDC MEASUREMENT TECHNIQUE

2.1 Theoretical Background

The PDC measurement principle is on the basis of applying DC voltage across the test object for a long duration. If a homogenous electric field $\mathrm{E(t)}$ is applied to the electrical material, the resulting current density through the material surface is [2-6]:

$$J(t) = \sigma . E(t) + \frac{d}{dt} D(t) \tag{1}$$

The current density $J(t)$ is the sum of the displacement and conduction current. σ is the DC conductivity and $D(t)$ is the electric displacement:

$$D(t) = \varepsilon_r \varepsilon_0 \cdot E(t) + P(t) \tag{2}$$

Therefore, from (1) and (2):

$$J(t) = \sigma . E(t) + \varepsilon_r \varepsilon_0 . \frac{\partial E(t)}{\partial t} + \frac{\partial P(t)}{\partial t}$$
(3)

Where, ε_0 is vacuum permittivity and ε_r is the relative permittivity of the insulation at power frequency. $P(t)$ is the dielectric polarisation related to the response function of the insulation material $f(t)$ which can describe the dielectric system's fundamental memory property.

$$P(t) = \varepsilon_0 \int_0^{\infty} f(t-\tau)E(\tau)d\tau$$
(4)

2.2 Polarisation and Depolarisation Currents

In order to investigate the dielectric material polarisation process, polarisation and depolarisation currents have to be measured. Combining all above equations:

$$J(t) = \sigma . E(t) + \varepsilon_0 \varepsilon_r \frac{dE(t)}{dt} + \varepsilon_0 \frac{d}{dt} \int_0^{\infty} f(t-\tau)E(\tau)d\tau$$
(5)

For a homogeneous material, an external voltage U(t) can generate E(t). Hence, the current through the test object with geometric capacitance of C_0 and measured capacity of C_m between the electrodes of the test object, where $C_0 = C_m/\varepsilon_r$, can be written as:

$$i(t) = C_0 [\frac{\sigma}{\varepsilon o} U(t) + \varepsilon_r \frac{dU(t)}{dt} + \frac{d}{dt}\int_0^t f(t-\tau)U(\tau)d\tau]$$
(6)

If the test object is fully discharged and if the applying step voltage have the following characteristics,

$$U(t) = \begin{cases} 0 & t < 0 \\ U_0 & 0 \le t \le t_c \\ 0 & t \ge t_c \end{cases}$$
(7)

For times before $t = 0$, the current will be zero and for $0 \le t \le t_c$ the polarisation current will be obtained. Therefore, polarization current through the test object can be expressed as,

$$i_p(t) = C_0 U_0 \left[\frac{\sigma}{\varepsilon_0} + f(t)\right]$$
(8)

The step voltage is then replaced by a short circuit, and the depolarization current is built up with the magnitude which can be expressed as,

$$i_d(t) = -C_0 U_0 [f(t) - f(t+t_c)]$$
(9)

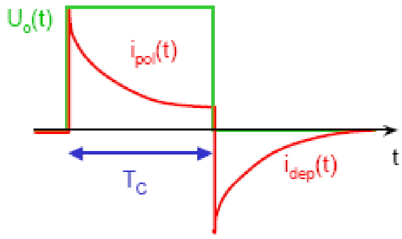

Figure 1: Polarisation and Depolarisation Waveforms [7]

where t_c is the charging time during which the voltage has been applied to the test object.

2.3 Dielectric Response Function

On the basis of the polarisation and depolarisation currents measurement, the general response function for oil or cellulosic insulation material can be obtained,

$$f(t) = \frac{A}{[\frac{t}{t_0}]^n + [\frac{t}{t_0}]^m}$$
(10)

Where A is the area of the electrodes of the test object, $t_0 > 0, m > n > 0$ and $m > 1$.
It can be assumed that the dielectric response function of the insulation material decreases with time. Since the dielectric response function changes proportionately with $i_d(t)$, for a sufficiently long duration of depolarisation,

$$f(t + t_c) \cong 0$$
(11)

Therefore, using (9),

$$f(t) = \frac{-i_d(t)}{C_0 U_0}$$
(12)

2.4 Conductivity Estimation

Once the polarisation and depolarisation currents are measured for a sufficiently long time, using (9) and (11), the DC conductivity of the test object can be estimated [2-6].

$$\sigma \approx \frac{\varepsilon_0}{C_0 U_0}[i_p(t) - i_d(t)]$$
(13)

The conductivity is relatively dependent upon the amount and the geometry arrangement of oil and paper inside the transformer. The polarization current contains two parts. The first part associates with the conductivity of the test object and the second part is related to the activation of the various polarization processes within the test object.

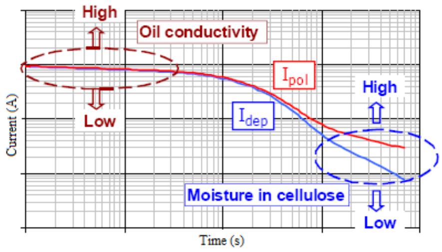

Figure 2: Interpretation of PDC measurement [7]

3 MEASUREMENT SETUP

3.1 Equipment

Keithley 6517A which is a highly sensitive electrometer has been used to measure the polarisation and depolarisation currents. Then the geometric capacitance between the two terminals of the test object is measured by Agilent 4263B for different testing conditions. The circuit switching is conducted using a HV switch and controlled by a computer. From the panel, the duration of the polarisation and depolarisation process along with the desirable DC voltage can be separately selected. The measurment setup is demonstrated in Figure 4.

Figure 4: Measurment setup

3.2 Basic Circuit

The circuit used for PDC measurement is shown in Figure 5. During the charging time, S1 will be closed while S2 should be opened. Once the charging time finished and the so-called polarisation current is captured and recorded, S1 will be opened and S2 will be closed automatically by the software so that the depolarisation current can be captured and recorded.

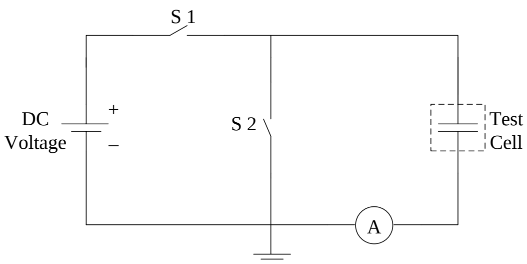

Figure 5: PDC measurement circuit

3.3 Test Cell

Since the oil moisture content can be easily affected by the surrounding environment, the test cell has been designed in such a way that it can prevent the ingress of moisture. Pressboards with 1.5mm thickness were used between the plates after being heated for 24 hours at 105 °C and submerged in oil for a week [8]. The test cell was placed in an oven where the temperature can be strictly controlled by a sensitive thermometer. The test cell is depicted in Figure 6.

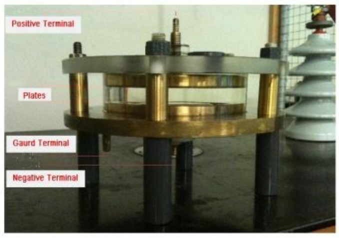

Figure 6: Test cell

4 TEST OIL

The test is conducted on mineral and bio-degradable oil which are directly taken from the barrel so that the moisture content of the test samples does not get affected. At 20°C which is the ambient temperature of the laboratory, the moisture contents of the normal mineral and bio-degradable oil are 31ppm and 170ppm respectively.

4.1 PDC Measurement Procedure

Once the test cell is filled gently with oil, it is placed in the oven. For temperatures higher than 20°C, a separate sensor was used to ensure that the oil temperature has increased to the desirable point. The duration of the polarisation and depolarisation process is set to be 10,000 seconds which is long enough for PDC measurement [9]. The testing voltage for the experiment is selected to be 1000V DC. Moreover, the response function parameters can be obtained using curve fitting function in MATLAB. To ensure consistency of the results, each test has been repeated several times.

5 EXPERIMENT RESULTS

5.1 Temperature Effect

The polarisation and depolarisation currents (log/log) for both types of oils under the effect of temperature are shown in the following figures.

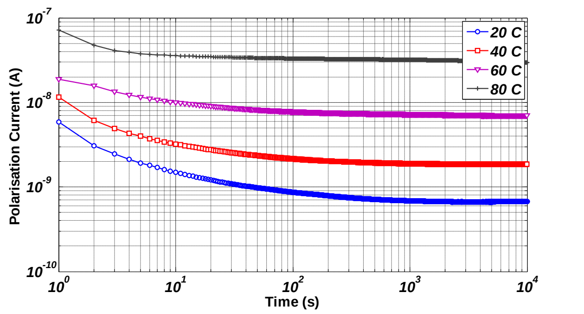

Figure 7: Polarisation currents for Diala BX under the effect of temperature (°C)

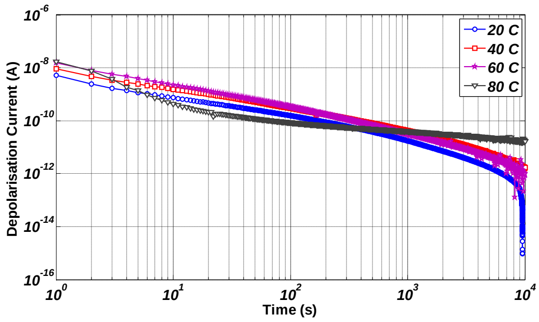

Figure 8: Depolarisation currents for Diala BX under the effect of temperature (°C)

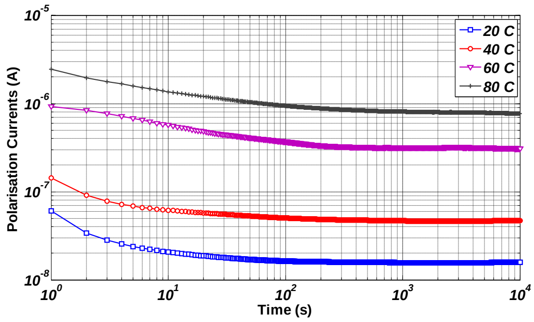

Figure 9: Polarisation currents for FR3 under the effect of temperature (°C)

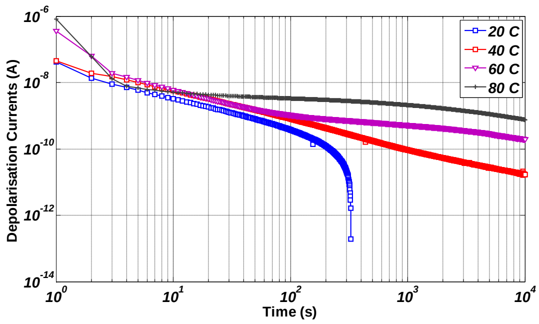

Figure 10: Depolarisation currents for FR3 under the effect of temperature (°C)

Generally, results show that the polarisation and depolarisation currents increase with temperature. However, the increase is more significant for polarisation currents. In both cases, for 20°C, depolarisation currents reach zero value before end of the test period.

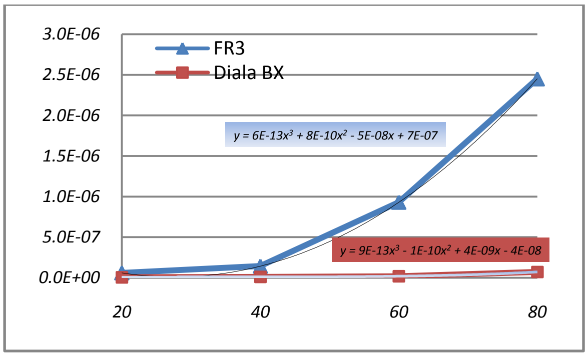

Figure 11: Variation of polarisation magnitudes with temperature (°C)

Figure 11 shows how the magnitudes of polarisation currents for both oils change with respect to temperature. As can be seen, polarisation pattern of FR3 is greatly affected by temperature. Also, when temperature rises, depolarisation currents reach their final values quicker. According to (13), maximum conductivities of the oil (*S/m*) samples have been calculated and gathered in Table 1.

Table 1: Variation of oil conductivity (*S/m*) at different temperatures

	Temperature (˚C)			
Oil	20	40	60	80
FR3	1.36e-11	8.05e-11	4.90e-10	1.40e-09
Diala BX	0.65e-12	2.34e-12	3.30e-12	4.70e-12

It can be seen that the conductivity of FR3 at different temperatures is significantly higher than Diala BX. This may be due to the reason that under the same thermal overstress, natural ester typically produces considerably more volume of gases [10-12].

The measured capacitance of the oil samples at various temperatures was found to have a different trend.

Table 2: Variation of measured capacitance C_m *(pF)* at Different Temperatures

	Temperature (˚C)				
Oil	20	40	50	60	80
FR3	62.13	54.10	53.1	52.40	51.60
Diala BX	49.70	50.40	50.5	50.70	51.40

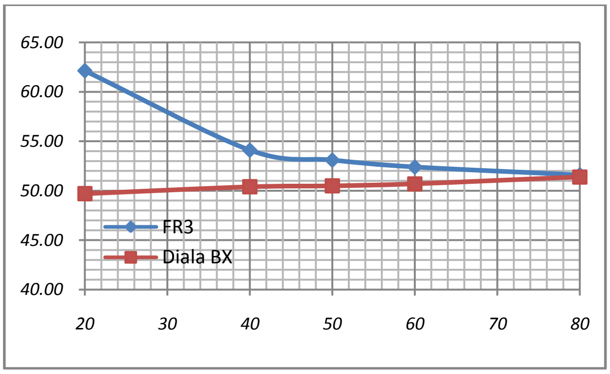

Figure 12: Variation of measured capacitance C_m *(pF)* at different temperatures (°C)

This can be due to the fact that the variation of dielectric constant of the two fluids is not similar when temperature rises [10].

5.2 Moisture Effect

To decrease the moisture content, the oil samples were dried under vacuum in an oil drying plant for 48 hours.

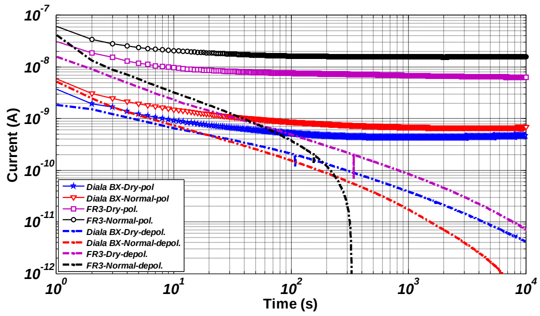

Figure 12: PDC spectrum for both oils under the effect of moisture

Figure 12 depicts that moisture has a considerable effect on PDC patterns. After the vacuum drying process, the magnitudes of i_{pol} and i_{depol} have been reduced. However, vacuum drying has been found to be more effective on FR3 of which the polarisation current amplitude is reduced by 51% compared to that of Diala BX (38%). The reduction in depolarisation current magnitudes was roughly similar for both FR3 and Diala BX (63%).

The maximum conductivity of each oil sample can be calculated for different temperature according to (13).

Table 3: Conductivity of oil samples (*pS/m)*

	FR3	Diala BX
Dry	11.4	1.6
Normal	15	1.9

The results show that the conductivity of FR3 has decreased by 24% compared to Diala BX conductivity which has reduced by 16%. This can be due to the fact that mineral oil has a low moisture saturation limit which drops as the temperature decreases while FR3 can absorb far greater amounts of water than mineral oil [13-15].

The water content in FR3 is higher than that normally found in mineral oil. This can be due to the chemical composition of the liquid causing it to be hydrophilic in nature. However, it may not adversely affect the dielectric strength since this is a function of the relative saturation of water in the dielectric liquid, not the absolute concentration. Also, new natural esters have inherently lower volume resistivity than mineral oil. Therefore, the relatively high conductivity found for all FR3 conditions can be due the higher level of moisture which can dissociate to ions resulting in increasing the conductivity. Also, the chemical makeup of natural esters has a slightly more polar character compared to mineral oil [16,17].

6 CONCLUSION

PDC experiments were conducted to establish the differences between the PDC patterns produced by both mineral and biodegradable oil at the different moisture and temperature levels. However, their behaviour under these effects was found to be different. The conductivity of both biodegradable and mineral oil increases with temperature. This means that higher temperatures and moisture contents exacerbate the condition of insulation. Vacuum drying was found to be more effective for FR3 since the reduction in its polarisation and depolarisation current magnitudes were higher.
The obtained results do not mean that high-voltage power transformers may not use natural ester fluid. It just implies that the design characteristics of high voltage equipment in natural ester are different from the commonly used for mineral oil. Natural esters are not as resistant to oxidation as mineral oils. The consequences of oxidation and hydrolysis can result in increase of acid numbers and viscosity as well as formation of polymerisation product. For this reason, the application of vegetable oil-based insulating dielectric fluids in free-breathing transformers is not recommended. However, biodegradable oil offers some advantages over mineral oil such as lower coefficient of expansion, higher heat capacity and thermal conductivity. Significantly high fire-ignition temperature of FR3 fluid can prevent transformer from ignition caused by arcing and sustained burning. In the case of spillage, especially in environmentally-sensitive areas, the biodegradability of natural ester liquids is an additional benefit.

7 REFERENCES

[1] Dielectric response methods for diagnostics of power transformers, *Electrical Insulation Magazine, IEEE*, vol.19, no.3, pp.12-18, May-June 2003

[2] T. K. Saha, P. Purkait and Z. T. Yao, ‘Condition monitoring of transformer insulation by polarisation and depolarisation current measurements,’ *in Australia Power Engineering Conference (AUPEC 02)*, Melbourne 2002

[3] M. Mirzaie, A. Gholami 2009, ‘ Insulation condition assessment of power transformers using accelerated ageing tests’, Turk J Elec Eng & Comp sci, vol 17, No. 1

[4] T. K. Saha, P. Purkait, "Investigation of polarization and depolarization current measurements for the assessment of oil-paper insulation of aged transformers," *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol.11, no.1, pp. 144- 154, Feb. 2004

[5] A. Bouaicha et al., "Dielectric spectroscopy techniques as quality control tool: a feasibility study," *Electrical Insulation Magazine, IEEE*, vol.25, no.1, pp.6-14, January-February 2009

[6] T.K. Saha, P. Purkait, "Investigations of Temperature Effects on the Dielectric Response Measurements of Transformer Oil-Paper Insulation System," *Power Delivery, IEEE Transactions on*, vol.23, no.1, pp.252-260, Jan. 2008

[7] M. Koch, S. Tenbohlen 2005, ‘Diagnostics of Oil-Paper-Insulations Using Relaxation Currents,’ Proceedings of the XIVth International Symposium on High Voltage Engineering, Tsinghua University, Beijing, China, August 25-29, 2005

[8] IEC60641-2, Pressboard and Presspaper for Electrical Purpose: Part 2: Method of Test, I. Commitees, Editor. 2004, International Electrotechnical Commission: Geneva, Switzerland. p. 13-27

[9] T.K. Saha, M.K. Pradhan, J.H. Yew 2007, "Optimal Time Selection for the Polarisation and Depolarisation Current Measurement for Power Transformer Insulation Diagnosis," *Power Engineering Society General Meeting, 2007. IEEE*, vol., no., pp.1-7, 24-28 June 2007

[10] T. A. Prevost, "Dielectric Properties of Natural Esters and their Influence on Transformer Insulation System Design and Performance," IEEE

[11] U. Biermann, J. O. Metzger, Application of Vegetable Oil-Based Fluids as Transformer Oil, Oleochemicals under Changing Global Conditiones, Hamburg, 25-27 February 2007

[12] "IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers," IEEE Std C57.147-2008, pp. 1-31, 2008.

[13] Y. Du, et al., Measurement of Moisture Solubility for Differently Conditioned Transformer Oils, in Proceeding of 13th International Conference On Dielectric Liquids (ICDL'99) 1999, IEEE: Nara, Japan.

[14] Power Online, Shell Lubricant, Products and services, Diala electrical oils, 2010

[15] Cooper, I.I., Envirotemp ® FR3TM Fluid, in Bulletin 00092 Product Information 2001.

[16] T.V. Oommen, "Vegetable oils for liquid-filled transformers," *Electrical Insulation Magazine, IEEE*, vol.18, no.1, pp.6-11, Jan.-Feb. 2002

[17] Envirotemp FR3 Fluid, Transformer Power Factor and Envirotemp FR3 Fluid, Cooper Power Systems, June 2009