DIELECTRIC CHARACTERIZATION OF CRUDE OIL EXTRACTS OBTAINED FROM DIFFERENT OIL FIELDS IN NIGERIA, INTENDED FOR UTILITY EXPLOITATION IN ELECTRICAL POWER TRANSFORMERS

[1]Akinnifesi, J. O, [2]Adebiyi, F.M. and [1*]Olafisan, K.F.
[1]Department of Physics and Engineering Physics Obafemi Awolowo University, Ile-Ife, Nigeria.
[2]Department of Chemistry, Obafemi Awolowo University, Ile-Ife, Nigeria.
(Corresponding Author e-mail: olafisankeny@oauife.edu.ng, GSM:08065768052)
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ABSTRACT

The utilization of liquid oils for electrical insulation has necessitated the dielectric characterization of oils. The conversion of excess crude petroleum oil to useful insulants constitutes an added advantage to the use of ever increasing crude oil production, as it enhances environmental pollution management. The different polar groups constituting liquid oil give rise to variation in dielectric properties. The respective values could be investigated to determine their sustainability in liquid insulants. The technique for the measurement of dielectric constants and loss factors has been most effective with the use of the Schering Bridge. In this work the modified Schering bridge circuit in association with a capacitive cell with the oil sample as dielectric, is used. Measurements were carried out at audio frequency and room temperature. The dielectric constants and loss factor of crude oil petroleum obtained from different locations in Nigeria are reported. The experimental values obtained compared favorably with reported literature values.

Keywords: Modified Schering Bridge, Crude Petroleum Oil, Dielectric Loss Factor, Electrical Power Insulation.

INTRODUCTION

The largest part of world's energy resources (about 85%) is derived from fossil fuel of which mineral oil in crude form is a major component. Crude oil is a mixture of naturally occurring hydrocarbon and non-hydrocarbon components in liquid form and most sought after as petroleum. Crude Petroleum consists of 10 to 13% weight hydrogen and 84 – 87% weight of carbon with traces of oxygen, sulphur, nitrogen and helium which may be present as impurities. Other constituents are paraffin, olefins, polymethylenes acetylenes, turpenes and benzenes (Yasin *et al.*, 2013). The physical properties vary largely in accordance to the percentage composition of the different constituents. Hence petroleum classification is usually based on its specific gravity, flash point and viscosity (Standing and Katz, 1942; Amyx *et al.*, 1960). From its initial application as a dielectric coolant, its use has been developed as insulators in several electrical equipment (Watson *et al.*, 1998; Eberhardt *et al.*, 2008). Consequently, to exploit the usage of the by-products of fossil fuel as insulation especially in electrical power transformers, the dielectric characterization of crude petroleum has come to the fore. This would also serve to reduce its environmental pollution occasioned by increase in its production (Nwangwu and Okoye, 1981). It would also complement effort at the utilization of petroleum byproduct by biodegradation and myco-degradation (Adekunle and Oluyode, 2005).

Dielectrics are broadly described in terms of relative permittivity or dielectric constant which is related to the electric polarization and conductivity. The loss factor is a measure of the dissipation of energy occurring in the material when subjected to an alternating electric stress and this affect its efficiency. Contributors to the losses include dipole orientation and ionic relaxation. The complex permittivity allows the evaluation of the electrical property and the analysis of the composition of the material. The special property of storage and dissipation of electrical energy when subjected to an electromagnetic field make characterization possible (Sugget, 1972; Coelho, 1979). This finds particular application in capacitors at radio-frequencies and in radio-frequency transmission optical fibres.

Another important property of the liquid dielectric is its breakdown voltage $V_{B.}$ This is defined by Baur's Law as:

$$V_B = A\sqrt[5]{t^2}\ V_B \qquad (1)$$

where t is the thickness of the dielectric and A is a constant depending on the nature of the medium, V_B determines the strength of the dielectric, an important parameter in the design of voltage generators, motors and transformers (Noto and Yoshimura,1974).

Central to the measurement of dielectric constant is the instrumentation technique. The dielectric constants of mineral oils have been previously measured using a PM 6302 RCL Schering Bridge operating on the basis of parallel plate capacitors. The values were reliably found to vary between 2.0 to 9.0 (Hartshorn *et al.*, 1957). The modified Schering Bridge has been mostly used for determining the dielectric constant and loss factor of crude petroleum oil. In this technique, the modification consists in minimizing measurement errors due to the effect of stray capacitance between the bridge output and lead wires. This is achieved by screening the bridge components and lead wires with Teflon (Bera and Chattapadhyay, 2003). Alternatively, air gaps formed between sample and conductor which can cause large measurement errors can be eliminated by the use of a pressure control system to press the sample. As the latter procedure is more suitable in the measurement of large values of dielectric constants (of the order of 100), the former modification procedure is applicable in our case. A further modification to this was the construction and integration of a capacitive cell with the possibility of electrodes immersion in the liquid samples for capacitance measurement. The simplicity, reliability and good repeatability of results obtained from the use of the Bridge technique has been confirmed by Tidar *et al.*, (2010) in the measurement of static dielectric constant of pure polar and non-polar liquids. An alternative approach to the modification of the Schering Bridge by the introduction of a shunt has been reported (Qianq, 1991). Moreover, use of the Schering Bridge to measure dielectric constant and loss factor of a dielectric material at microwave frequencies has been reported (Kumar *et al.*, 2007).

In general, the dielectric thermal analysis of a liquid material which measure permittivity at a set frequency and voltage at a given temperature is often used and is the method adopted in this work. The method is more efficient and simple and will be used by means of the modified Schering Bridge to measure the dielectric properties of crude petroleum oil samples extracted from different oil fields in Nigeria. This would provide the opportunity to exploit the potential of the abundant by- product of crude oil for use as insulation in electrical power transformers.

MATERIALS AND METHOD

(a) Instrumentation Basis

For the dielectric characterization of materials, the dielectric thermal analysis (DETA) can be used in accordance with the American Standard for Testing Materials (ASTEM – E2038) procedures. In a typical test, the sample is placed in contact with two electrodes which constitute the dielectric sensor and a sinusoidal voltage, which is the excitation, is applied to one of the electrodes. The resulting sinusoidal current is measured at the second electrode. The response signal is attenuated in amplitude and shifted in phase in relation to the mobility of the ions and alignment of the dipoles. The dielectric properties of permittivity and loss factor can then be calculated from the measured amplitude and phase change. The characterization can be done as a function of voltage and set frequency at a given temperature or as a function of temperature at a given frequency. In this work we opt for the frequency domain technique and employ the modified Schering Bridge coupled to the parallel plate capacitance cell with our sample as the dielectric. The schematic illustration of the Bridge is given in Figure 1. It can be used to measure the capacitance, dissipation factor and relative permittivity of a capacitor. In the figure, c_1 is the unknown capacitance to be determined, associated with a series electrical resistance r_1.

A standard capacitor c_2 is contained in an adjacent arm while a variable capacitor c_4 is connected with a pure (non-inductive) variable resistor r_3. A low voltage AC generator is applied to the bridge between the points *a* and *c* while the detector D links the bridge between the points b and d. The detector indicates the balance point between the arms of the bridge. The four arms are represented by e_1, e_2, e_3 and e_4 . If z_1, z_2, z_3 and z_4 are the corresponding impedance of the bridge arms, at balance condition, then

$$z_1 z_4 = z_2 z_3 \quad (2)$$

Substituting the impedance values, equation (2) becomes

$$\left(r_1 + \frac{1}{j\omega c_1}\right)\left(\frac{r_4}{1 + j\omega c_4 r_4}\right) = \frac{r_3}{j\omega c_2}$$

$$\text{or } r_1 r_4 - \frac{jr_4}{\omega c_1} = -\frac{jr_3}{\omega c_2} + \frac{r_3 r_4 c_4}{c_2} \quad (3)$$

Equating the real and imaginary parts of this, we have

$$r_1 = \frac{r_3 c_4}{c_2} \quad (4)$$

$$\text{and } c_1 = \frac{c_2 r_4}{r_3} \quad (5)$$

The phasor diagram would yield the dissipation or loss factor, i. e.

$$\tan\delta = \omega r_1 c_1 \quad (6)$$

Substituting (4) and (5) in (6), we obtain

$$\tan\delta = \omega c_4 r_4 \quad (7)$$

Thus the dissipation will increase as the frequency increases.

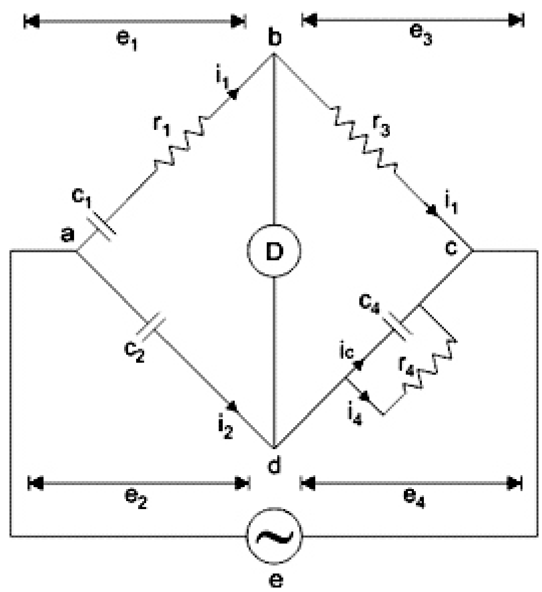


Fig.1: Schematic Circuit of the Schering Bridge

To measure the relative permitivity ε_r of our sample, the unknown capacitative c_x of the capacitor, with the specimen as dielectric is first determined from the simple relation.

$$Cx = \frac{\varepsilon_r \varepsilon_0 A}{d} \quad (8)$$

where d is the inter-electrode spacing and A is the plate area, ε_r is the relative permittivity and ε_o is the permittivity of free space.

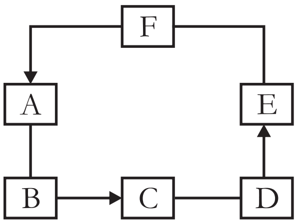
For air $\varepsilon_r = 1$, hence

$$Cx = \frac{C_{air} d}{A} \quad (9)$$

(b) Sample preparation and characterization

Raw samples of crude oil were extracted from three different oil fields, denoted C_1, C_2 and C_3 respectively for the oil fields of Ogoni in Rivers State; Belema in Balyesa State and Sapele in Rivers State, all in Nigeria. The appropriate component of the crude oil was obtained by fractional distillation. The capacitive cell was constructed from parallel plates of aluminium electrodes 15 cm by 15 cm in dimension. These were connected together at a separation 2 mm using Teflon around the connecting bolts to avoid short circuiting. Connecting wires were screwed and soldered to each of the electrodes. The arrangement was subsequently immersed in a previously rinsed beaker containing the liquid dielectric. The electrodes were then connected to the two terminals of the Bridge. The two ends of the detector in the Schering Bridge were also connected to the Oscilloscope. This allowed the determination of the balance point and the measurement of the signal generated as the resistor in the Bridge was varied. The Bridge has the advantage that the balance point depends not on the frequency but only on the arms impedance. As such the frequency domain applied was audio frequency (about 100 MHz), which was audible at balance point. Thus two arms of the Bridge were fixed while the third arm was varied for measurement of the fourth arm. Though low frequency dielectric measurement techniques have been reported to be time consuming (Setayeshmehr *et al.*, 2008), more premium was placed on the reliability and reproducibility of data. Beside, measurement of dissipation factor of tested oils with temperature variation showed increased values while the dielectric constants decreased as reported by Rajab *et al.* (2011).

The accuracy of the modified bridge was ascertained with 4 known capacitances, each connected in series with the loss resistance in one arm at applied voltages of 100 – 600 V in audio frequency. A similar procedure was followed to further determine the efficiency of the bridge using several other known materials as dielectrics between the capacitor plates.



A: Audio frequency AC signal generator
B: Variable DC power supply
C: Capacitive cell immersed in oil sample
D: Cathode ray oscilloscope
E: Capacitance meter
F: Modified Schering Bridge.

Fig. 2: Schematic Circuit Flow diagram of the Capacitance Measurement Technique

The capacitance cell filled with the oil under test was measured by applying an electric power to the cell. The output signal was fed to an oscilloscope and was read from capacitance meter.

The relative dielectric and permittivities losses for the various oil samples were determined from their measured capacitance using equations (7) and (9) respectively. Three consecutive measurements were taken in each case and the mean was recorded. It is interesting to note that each of the several measurements differed by not more than 2.5% of the highest value, which underscored the efficiency of the modified Schering Bridge. Care was taken to avoid measurement error in the liquid dielectrics by preventing the occurrence of the undue velocity gradient in the molecules of the liquid. This is due to the fact that low rate of shear could lead to large rates of increase in dielectric constant (Funt and Mason, 1951).

RESULTS AND DISCUSSION

Capacitance measurements of known capacitors of values 560 pF, 8200 pF and 3300 pF were carried out, in order to check the accuracy of the modified Schering Bridge capacitance meter. Table 1 shows the results of the dielectric constant measurement.

Table 1: Measured capacitance values of known capacitors using the modified Schering Bridge

Nominal Capacitance of known Capacitors (pF)	Experimentally measured value of the Capacitance (pF)	Percentage Error
7560	7580	+1.5
8200	8500	+2.6
3300	3400	+2.0

These are in fair agreement with the reference values of the nominal and measured capacitances. Further efficiency check of the modified bridge was ensured by determining the relative permittivity of wax, paper, diesel fuel, ethanol and water at ambient temperature as presented in Table 2.

Table 2: Relative dielectric permittivities of various materials at ambient temperature obtained from the modified bridge vis a vis their reference nominal values.

Material	Reference value of ε_r	Measured capacitance (pF)	Measured value of ε_r
Wax	1.80	227.26	1.70
Diesel fuel	2.10	294.10	2.20
Paper	3.50	427.78	3.20
Ethanol	25.00	2420.46	24.30
Water	78.50	3248.46	77.30

From the table, the measured values were observed to be close to the reference values for the respective materials, though the reference values varied from one source to the other. The capacitance of the test cell filled with the respective oil samples, Cx and the capacitance, filled with air as dielectric Co were obtained. The relative permittivity was determined in accordance with the equation $\varepsilon_r = \frac{C_x}{C_0}$ constituting the dielectric constant. The mean of three consecutive measurements for each of samples C_1, C_2 and C_3 are plotted in function of the applied voltages as presented in Figure 3.

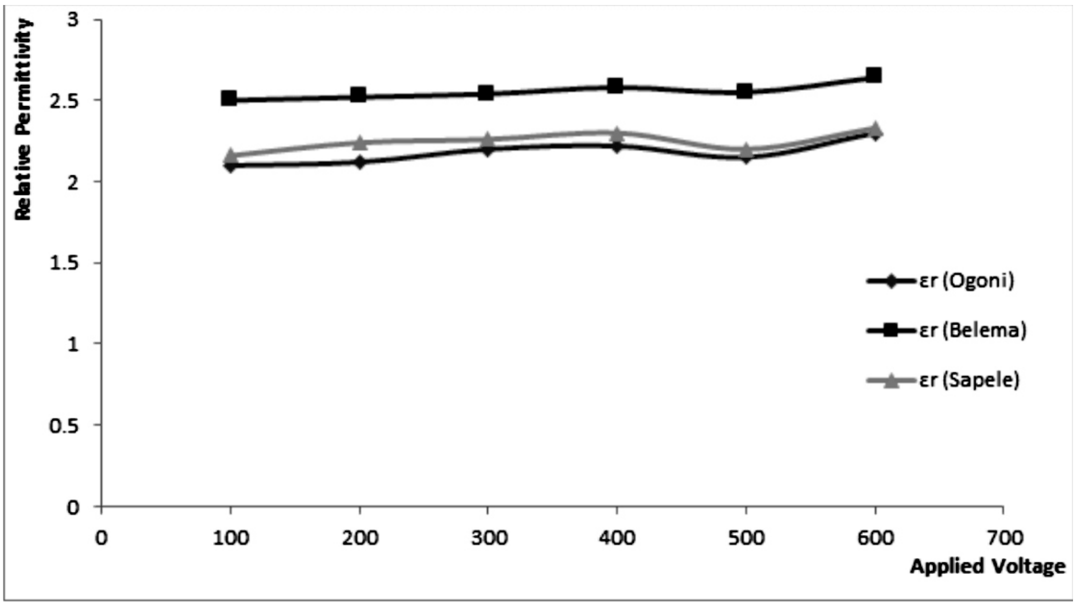


Fig. 3: Relative Permittivity as a function of Applied voltage

The permittivity spectra are characterized by kinks occurring at an applied voltage of 500 V, and are slightly more conspicuous on the Ogoni and Sapele oils. The kinks may have resulted from dielectric relaxation mechanisms occurring at 500 V, 50 Hz.

The average values of relative permittivity of the three different samples were found to be 2.56, 2.16 and 2.21 for the Belema, Ogoni and Sapele oil respectively. The values are quite close for Ogoni and Sapele oils. For all three samples, these values fall within the reported values of 2.0 – 9.0 in the literature, for oils useful as dielectrics in electrical power transformers.

Similarly the dielectric dissipation or loss factor, tan δ was determined from the mean of three consecutive measurements for each of the three different sample types for various applied voltages. The results are plotted in Figure 4 as a function of the applied voltage.

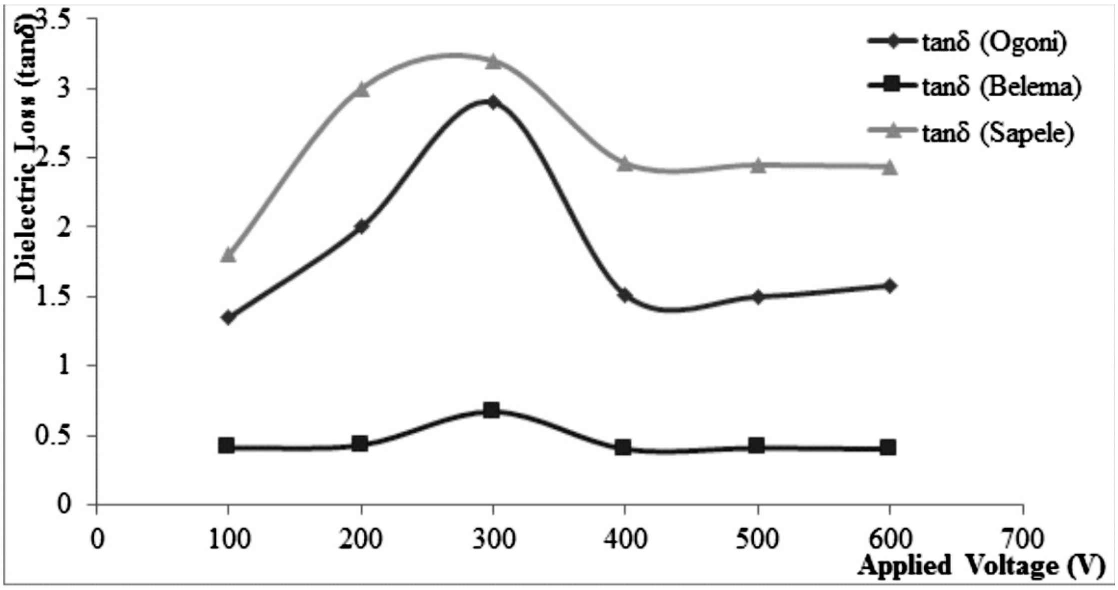


Fig.4: Dielectric Loss as a Function of Applied Voltage in the Three Different Oil Samples

The peaks observed at 300 V, 50 Hz for the Ogoni and Belema oils and also at 250 V, 50 Hz for the Sapele oil could be explained by the phenomenon of increase in leakage current and maximum dissipation of energy, occasioned by low frequency dipole relaxation occuring at those points.

The electrical stress for the measurement was calculated from the ratio of maximum applied voltage to the critical distance between the two electrodes, giving:

$$E = \frac{0.6kV}{2mm} = 0.3\,\text{kV/mm}$$

This was observed to be within the normal range 0.03 – 1 kV/mm of the standard electrical stress for tan δ measurement in oil, in accordance with established values (IEC, 2004).

CONCLUSION

The measurement of dielectric properties of oil is necessary for its exploitation for use as insulation in electrical equipment. The relative permittivity is one of the most important parameters to be considered in choosing a suitable liquid insulation. The Schering Bridge coupled with parallel plates capacitor was found suitable for determining the unknown dielectric constant of oil with considerable accuracy. The bridge had the advantage that the balance point depended not on the frequency but only on the arms impedance.

Nigerian crude oil samples obtained from different locations were characterized by means of the Schering Bridge. Their relative permittivities and dielectric losses were measured. The reliability of the measurements was ensured by carrying out test measurements of dielectric constants on several samples whose reference values of the dielectric constant were known. A fair accuracy in the bridge measurements was obtained. The measured permittivity values of the oil samples were averagely found to be 2.56, 2.16 and 2.21 for Belema, Ogoni and Sapele crude oil samples respectively. The values fall within the range useful in electrical power transformers.

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