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On the physical significance and di-electric response of Castor oil processed in Nigeria as transformer insulating fluid

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Abstract: - In view of castor oil as non-toxicity and good di-electric properties which can be used as dielectric fluid inside transformer. Castor oil, a polar liquid dielectric of vegetables origin is studied. This paper presents a description of frequency domain dielectric response technique with the physical and mathematics background.

The measurements were made using the L-C-R meter connected by co-axial cable and signal generator. Relative permittivity of castor oil was determined at frequency ranging from 25Hz to 150 KHz and temperature ranging from 27^0C to 100^0C.

The data obtained have been statistically analysed. It was observed that the real part of the relative complex permittivity was frequency independent. It also shows that there is a slight deviation between complex permeability of the oil sample and temperature increases compared with the result of typical transformer oil.

I. Introduction

Transformer that are normally use in electric domain are of a homing type and the distribution transformer selection, whether for residential, commercial, industrial, or utility application, has long-term ramifications. Transformer can have live span of 15, 30 and even 50 years or more, depending on their design, loading, application, protection, and maintenance. It is important to evaluate all the transformer attributes that effect the purchase decision. (Paranjpe etal., 1935). Liquid-filled transformer are often not considered as an option for indoor installations due to historical issues of fire safety, environment concerns, and special containment. Because of these perceptions, vacuum pressure impregnates (VPI) dry-type and cast-resin transformer have often replace liquid-filled transformers for indoor and adjustment to building installations (Dervos et al., 2005). With this trend, significant advantages like superior life, efficiency, sound level, overload capacity, contamination resistance, and online diagnostics which are characteristics of liquid transformers have been lost Safety and environmental issues have been improved due to changing in the transformer fluids and listing requirements, so that the benefits of liquid-filled transformers can be retained for indoor and adjust to building installation (Cigke, 2005).

Since the 1970s, the public has been sensitized to the polychlorinated biphenyl (PCB) based transformer oils. In 1976, the Toxic Substance Control Act targeted PCB. The beginning of further production and commercialization of PCBs, and increasingly restrictive Federal and state regulations, led to the introduction of other fire-resistant transformer types. While most PBC oil filled transformers have been replace with PCB free mineral oil, fire resistance hydrocarbon fluids, or silicone oil, the replacement fluid have still not been environmentally preferred (Nozaki, 2005). Vegetable oils are increasingly used in the electrical industry as an insulator since they are non-toxic to the environment, biodegradable if spilled and have high flash and fire points. Vegetable oils. However, have to be traded-off their benefits with biodegradable characteristics. Thus, they are generally used in system with no exposure to the atmospheric oxygen. (Boonchoo, 2007)

Highly insulation oil used to suppress partial discharge, increase the dielectric strength and increase the effective permittivity (dielectric constant) of the capacitor die-electric (Nozaki, 2005) Oil-filled film capacitors used at high voltage, such as ceramic capacitors (Rawlins, 1985).

Vegetable-oil based insulating fluid has not been accepted because of their high pour point and inferior resistance to oxidation relative to mineral oil they. We are also believed to be more expensive compared with the mineral oil has been in use for electrical insulation in transformers and other oil-filled electric equipment. With recent frequent increase in the prices of petroleum and uncertainly concerning petroleum products availability, accelerated research and development are on around Nigeria in search for alternative to petroleum products. Part of this is a renewed interest in the use Groundnut oil, Cotton seed oil soyabean oil and castor oil as industrial insulating fluid since this is yielding positive result in some other part of the world, but their viscosities are lower than the castor oil (Schneuwly et al., 1990). Also, castor oil has hydroxide content of about 5%, is an important polysaccharide reagent. The chemical composition of this unsaturated oil which has a high relative permittivity between 4.2 and 4.5. Castor oil has therefore found wide application as impregnating agent in power capacitors such as transformers (Boonchoo, 2007)

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The quality of the insulating transformer oil is periodically investigated. The typical electrical tests cover the determination of the electric strength i.e., the voltage reached during the test t the time first spark occurs between two electrodes (breakdown voltage) (Derdos et al., 2005). The electric strength is not a criterion of insulating oil manufacturing quality but is rather a conventional test intending to reveal the extent of physical contamination by water and other suspended matter and the advisability of carrying out drying and titration treatment before the oils are introduced into the transformers.

There is a great demand in using dielectric diagnostic method to relate the electrical purity state of oil to their insulation properties. Recent attention has being focused of measuring various dielectric response parameters, which characterize some known polarization phenomena, the three foremost techniques are (1) Recovery or return voltage measurements (RVM), (2) Dielectric spectroscopy in the domain, i.e. measurements of polarization and depolarization depolarization current (PDC), and (3) Dielectric frequency domain spectroscopy (FDS), i.e., measurement of electric capacitance C and loss factor (tan8) in dependency of frequency.

Various experiments were carried out with all the techniques on insulation model and the results confirmed that the dielectric response measurements provide valuable information on the state of oil insulation on power transformers. (Cigke, 2003). All of the compared dielectric response methods (RVM, FDS, and PDC) reflect the same fundamental polarization and conduction phenomena in transformer insulation.

The present study applies frequency Domain Dielectric Response techniques as a diagnostic tool on the possible selection of castor oil for transformer and other Oil-filled electric equipment. The possible life span of the dielectric constant data was also investigated.

Figure 1 : Castor oil (Triricinolein, C_3H_5 $(C_{18}H_{33}O_3)_3$.) seed

II. Theoretical considerations

Measurement using Dielectric Response Methods are based on fundamental interaction between well-known electric quantities (Zaengl, 2003) usually, Insulation materials are isotropic and usually homogenous, at least at macroscopic polarization *P* and the electric field *E* are of equal direction and related by

$$P = \varepsilon_0 (\varepsilon - 1) E \quad (1)$$

Where ε_0 and ε are the permittivity of vacuum and dielectric materials respectively. In a vacuum insulated electrode arrangement, the vector of electric displacement (or dielectric flux density or electrical induction) *D* is generated by a time-varying voltage,

$$D(t) = \varepsilon_0 E(t) \quad (2)$$

Where ε_0 again the permittivity of vacuum

If the vacuum is now replaced by any kind of *isotropic* dielectric material, the electric displacement *D* of equation (2) increases by its inherent (macroscopic) polarization *P* as defined in equation (1):

$$D(t) = \varepsilon_0 E(t) + P(t) = \varepsilon_0 \varepsilon_r e E(t) \quad (3)$$

Where ε_r is the relative permittivity of dielectric material. The dielectric polarization *P*(t) is related to the response function *f*(*t*) of the material by the relation

$$P(t) = \varepsilon_0 \int_0^\infty f\,(t - r)\,e\,(r)\,dr. \quad (4)$$

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If applied electric field E(t) to the dielectric material is assumed to be homogeneous, the current density through the surface of the material can be written as:

$$j(t) = \sigma_0 E(t) + \frac{dD(t)}{dt} \quad (5)$$

$$j(t) = \sigma_0 E(t) + \varepsilon_0 \frac{dD(t)}{dt} + \frac{dP(t)}{dt} \quad (6)$$

Substituting equation (4) in (6), the current density can be written as

$$j(t) = \sigma_0 E(t) + \varepsilon_0 \frac{dE(t)}{dt} + \varepsilon_0 \frac{d}{dt} \int_0^1 f\ (t-r)E(r)dr \quad (7)$$

Transforming equation (7) from time to frequency domain with

$j(t) \rightarrow j(p)$; $E(t) \rightarrow E(p)$; $E'(t) \rightarrow pE(p)$; $f(t) \rightarrow F(p)$

And convolving the last term in this equation we get, with p being the Lap lace Operator:

$$J(p) = \sigma_0 E(p) + \varepsilon_0 pE(p) + \varepsilon_0 pF(p)E(p) \quad (8)$$

As p is the complex frequency iω, we can reduce equation (7) to

$$j^*(\omega)=E^*(\omega)\ \{\sigma_0+i\omega\varepsilon_0 [1+F^*(\omega)]\} \quad (9)$$

thus F* (ω) is the Fourier Transform of the dielectric response f(t) or the complex susceptibility:

$$x^*(\omega) = F^*(\omega) = \int_0^\infty f\ (t) \exp(-i\omega t)dt \quad (10)$$

But

$$x^*(\omega) = \varepsilon^*(\omega) - 1 = \varepsilon`(\omega) - i\varepsilon``(\omega) - 1 \quad (11)$$

Combining equations (9) and (11), the total current density is:

$$j^*(\omega) = \{ \sigma_0 = i\omega\varepsilon_0[\varepsilon`(\omega) - i\varepsilon``(\omega)\}\ E^*(\omega) \quad (12)$$

The main part of this current has its origin in the complex electric displacement D*(ω) which is proportional to the complex dielectric permittivity, ε* (ω), with the relation:

$$D^*(\omega) = \varepsilon_0\varepsilon^*(\omega)\ E^*(\omega) \quad (13)$$

Actual measurements of this dielectric response in the frequency domain are usually difficult to perform, if the frequency range becomes very large. However, sophisticated modern laboratory instruments are now available that can cover even many decades in frequency (Obizcut, 2005) Note, that according to equation (12) such instrument cannot distinguish between the current contribution of the "pure" conductivity σ0 and that of the dielectrics loss ε``(ω). This means that the measured relative dielectric permittivity $\varepsilon_r^*(\omega)$ is different from the relative permittivity ε*(ω) defined from the following relation:

$$j^*(\omega) = i\omega\varepsilon_0\varepsilon^*_r(\omega)E^*(\omega) \quad (14)$$

Therefore:

$$E_r^*(\omega) = \varepsilon`_r(\omega) - i\varepsilon``_r(\omega)$$

$$= \varepsilon`_r(\omega) - i\ [\varepsilon``_r(\omega) + \sigma_0\varepsilon_0\omega] \quad (15)$$

and the dielectric dissipation factor, tanδ(ω),

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$$\tan\delta(\omega) = \frac{\varepsilon``r(\omega)}{\varepsilon`r(\omega)} = \frac{\varepsilon``(\omega) + \sigma o/\varepsilon o\omega}{\varepsilon`r(\omega)} \quad (16)$$

The real part of equation (15) represents the capacitance of a test object, whereas the imaginary part represents the losses. Both quantities depend on frequency. They are also dependent on temperature. The dependence of dielectric permittivity, of dielectric on temperature is estimated (Nosaki *et al.*, 2005) by means of the temperature coefficient of permittivity.

$$\tau_{\varepsilon} = \frac{1}{\varepsilon}\frac{d\varepsilon}{dT} \quad (15)$$

III. Experimental

Castor seeds were harvested from the wild, dried, crushed and separated into seeds and shells. The seeds were packed into the extraction chamber and normal hexane poured into the round bottom flask of a Soxhlet extractor or compressed machine.

An LCR meter (Philips PM 6303) was used to measure the complex permittivity in frequency range between 40 Hz and 160 KHz. A designed cylindrical liquid cell machined to precision was to host the oil under test. It was located inside an oven (PID-200 controlled Oven) that was powered by DC power supply (TypeLAB59R). The measuring cell contained about 7.5 ml of the test liquid and was connected by a coaxial cable to the LCR measuring unit. A signal generator (Philips PM51 L.F1frequency generator) was equally attached to the RCL Bridge using a coaxial cable to vary the frequency; block diagram and the complete figure shown in Figure 1 and 2 respectively.

1. Sample under test (cell)
2. Philips' PM 6302 RCL Bridge
3. Philips' PM 5165 L.F signal generator
4. Coaxial cable

Figure 1: Block diagram of the experimental set up

Figure 2: LCR meter

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IV. Result and discussions

For the purpose of this study, measurements were performed at frequency ranging from 25 Hz to 160 kHz and temperature ranging from 27^0c to 100^0c.

The measurement is taken 3 and 6 times in same sample of oil and the average value of these reading is taken. According to the experimentally obtained results, the real part of the relative complex permittivity ($\varepsilon`_r$) is frequency independent (table 2) while as the temperature of the oil sample increases, the real part of the relative complex permittivity ($\varepsilon`_r$) tends to decrease (Table 1).

According to the theoretical model enabling permittivity evaluation of materials versus frequency and temperature (Rawlins, 1985), it can be concluded that good quality castor oil samples will be characterized by low relative complex permittivity ($\varepsilon`_r$) values (practically measured in the range of 4.5) and low $\varepsilon``_r$ values (and, therefore, tanΘ, which in practices is measured in the range of 10^{-3} to 10^{-4} at all frequencies.) The values obtain for the relative permittivity of castor oil usual support the statement of stoops (Deshpande, 1997) that reasonably moments of vegetable oils should have values in the range 2.7 to 4.5 in the absence of polarization processes, these results show that it is temperature independent, implying that the examined samples are high purity castor oils being entirely free of contaminants.

Table 1: Effects of frequency on the relative permittivity of castor kernel oil sample at room temperature.

Frequency (Hz)	Relative Permittivity (ε_r)*
25	4.49
200	4.48
500	4.48
1000	4.49
2000	4.48
3000	4.48
4000	4.47
5000	4.47
6000	4.48
8000	4.48
10000	4.48
11000	4.47
12000	4.48
13000	4.48
14000	4.47
15000	4.48
16000	4.47

Table 2: Effect of frequency on the Relative permittivity of Castor oil sample.

Temperature (ºC)	Relative Permittivity
20.00	4.45
30.00	4.00
40.00	4.50
50.00	3.19
60.00	2.89
70.00	2.68
80.00	2.60
90.00	2.53
100.00	2.50

‘* *means of triplet value of the Relative Permittivity*

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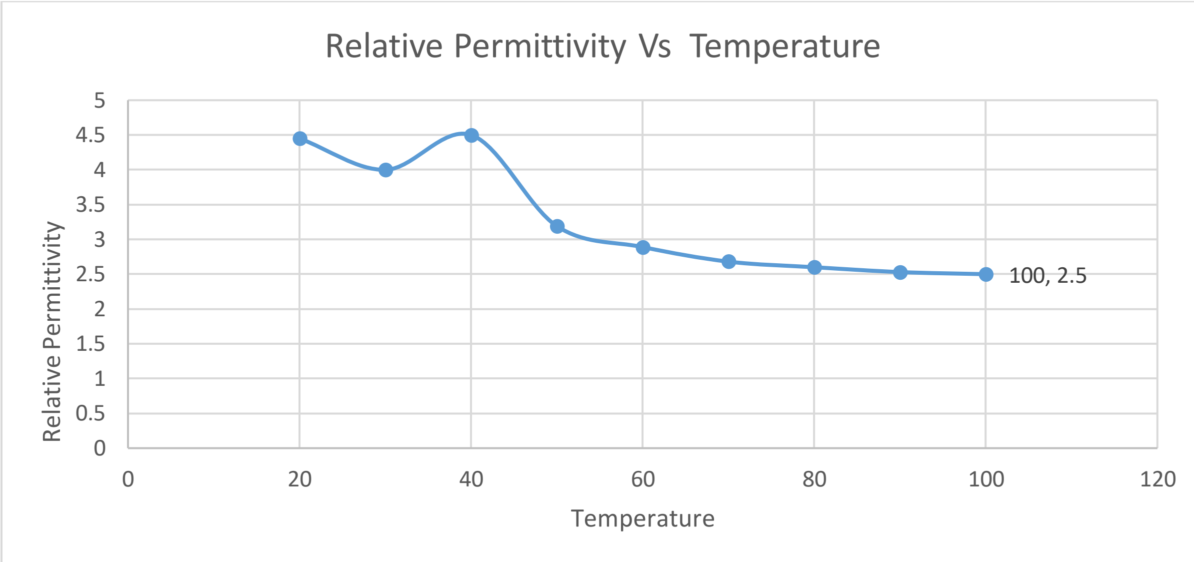

Frequency was found to have no effect on the sample under study. When there is no electric field been present, the molecules are randomly orientated, and no net charge exists in the material. However, when a field is applied to dipoles will rotate cancelling part of the applied field and leading to an orientation polarization. The rate of oscillation of the applied field is a function of the frequency (Taeev, 1975). At low frequencies, the oscillation of the applied field is very slow, and the molecules have enough time to fully rotate as a result, minimal energy is dissipated and no dielectric loss and hence no observed change in the real part of relative permittivity value of the oil sample. Electronic and atonic polarization mechanisms are equally small at low frequency due to effect of inertia of the orbiting electrons. (Zaengil, 2003).

The dependence of the complex permittivity on temperature was due to effect of temperature on the polarization mechanisms. (Cigke, 2003). Electronic polarization is relatively unaffected by temperature. However, atomic polarization is affected since the binding forces between ions or atoms changes with temperature. Highest losses are encountered at the highest temperature values. The result shows that temperature increase induces the worst case operating electrical conditions (i.e., highest breakdown probabilities). Meanwhile, there was a slight deviation in the relationship between complex permittivity of the oil sample and temperature increases compared with the results of typical transformer oil. This could be as a result of the presence of high level of ionic conducting solids in the oil sample.

V. Conclusion

The monitoring of the complex permittivity of material, as a function of frequency and temperature, may provide insight information concerning the state of the insulation status of commercially available castor oil. The result of the investigation shows that the oil sample has slight deviation compared with the behaviour of typical transformer oil. But if properly purified to transformer oil grade and necessary additives added, it has the potential of serving as insulating fluid in oil-filled electric equipment. Work is however in progress to develop a Nigerian processed as previous investigations on groundnut oil, cottonseed oil, and soybean oil shows promising result (Tareev, 1975). Successful development of such seed oil-based transformer oil will eradicate the environmental threat posed by mineral oil because of possible accidental leaks or fires, especially when containing traces of PCBs. It will also eradicate the continuous dependence on petroleum product for insulation.

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