EXPERIMENTAL STUDY OF ELECTRICAL PROPERTIES OF MINERAL AND VEGETABLE TRANSFORMER OILS

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The flow electrification of mineral oil produces local electric discharges which may worsen the physico-chemical properties of the electrical power transformer insulation systems and facilitate their damage, which may lead to interruptions in the power supply. This paper presents a study concerning the link between the primary dielectric properties of mineral and vegetable transformer oil and their charging tendencies. For this purpose, the flow electrification current has been measured with a spinning disk system on mineral and vegetable oil samples (used in electrical power transformers insulation systems). The results show the existence of a correlation between the oils' electrical properties and the surface charge density located at the oil/ pressboard interface in a time unit. Also, it is found that the surface charge density located at the oil/ pressboard interface in a time unit increases if the value of the real part of relative permittivity increases, respectively if the oil's resistivity decreases.

Keywords: vegetable oil, mineral oil, power transformers, electrical charging tendency, flow electrification phenomenon

1. Introduction

Power transformers are the most important equipments that are part of the power transmission and distribution grids. Part of the power supply interruptions are due to the defects that occur to these equipments, especially to their insulation systems. Most of the power transformers have cellulose paper and oil (it can be mineral, vegetable or silicone oil) based insulation systems [1].

Mineral oils, used as coolant insulating fluids in power transformers, are obtained by petroleum distillation (after separating the light products, like benzene), and followed by treatment with sulfuric acid refinery. From a chemical point of view, mineral oil is a mixture of naphthenic (> 60%, very stable molecules with low freezing points), aromatic (< 30%, contains a high number of

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carbon atoms which can be released under the action of the electric discharge thereby worsening the oil's properties), and paraffinic (< 30%, they have high freezing points) hydrocarbons. The final properties of the mineral oil depend on the chemical composition [2].

On the other hand, vegetable oils belong to a group of organic compounds which are generated by the reaction of an acid with the alcohol. Fats and oil emerge from esterification of glycerin and fatty acids. The name "fatty acid" is a collective term for mono-carboxylic acids, which consist of a carboxyl group (-COOH) and of a variable long, but nearly exclusively unbranched hydrocarbon chains [2]. Vegetable oils are natural ester molecules with a triglyceride structure, originating from the chemical linkage of three fatty acids to one glycerol molecule [3].
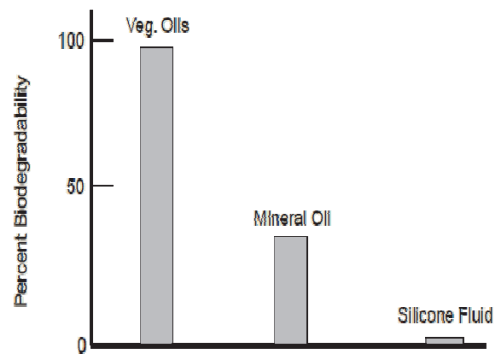

Fig. 1. Degree of biodegradability [2].

Today, there is an increasing interest in the use of vegetable oils rather than mineral oils for both distribution and power transformer applications. This is mainly due to the following advantages of vegetable oils compared with mineral oils:

- vegetable oils have a high fire-point (> 300°C) as compared to mineral oil (< 200ºC), which contributes to increased fire-safety for vegetable oil filled transformers.

- vegetable oils have high biodegradability (Fig. 1), therefore they are more environment-friendly.

- vegetable oils have a higher affinity for moisture. A higher moisture saturation limit will keep the paper more dry (as compared to the mineral oil case) in a transformer and therefore can prolong the life of the paper insulation in the transformer under normal operating conditions.

It has been seen that some vegetables oils have higher acidity and higher viscosity from oxidation stability tests as compared to the results obtained for mineral oil [4]. As a matter of fact, the oxidation behaviors are dependent on the

chemistry of the vegetable oils and high oleic vegetable oils are observed to have reasonably good oxidation behaviors [5].

During operation, the insulation of a power transformer is permanently subjected to electrical, thermal and environmental stresses. Under overloaded conditions, the chemical degrading reactions of mineral oil and cellulose based components intensify and the resulting reaction products can lead to the worsening of the dielectric properties of the equipment's insulation system [6].

The degradation reactions that occur in the mineral oil are oxidation, dehydrogenation and the cracking reaction (which leads to C-C bonding fracture, with the formation of alkenes). Oxidation and hydrolysis are the degradation reactions which occur in the vegetable oil, leading to the formation of CO, CO_2, water and acids. Also, in the oil are present the degradation products resulted from the paper degradation (CO, CO_2, water and furans) [7].

Further, research conducted on damaged large power transformers have also concluded that the oil's electrical charging tendency (ECT) is another factor that can contribute to the degradation of the insulation [8, 9]. The charging tendencies in the transformer are attributed to the physico-chemical processes that are taking place at the separation surface between the oil and the solid components of the equipments (both the metallic components and the cellulose-based materials) [8, 9].

When a solid is in contact with a liquid, the initially neutral liquid-solid system is polarized as a result of the physico-chemical processes that are taking place at the solid/liquid interface [10]. This phenomenon, no matter the nature of the two materials, leads to the formation of an "electrical double layer" (a double layer of charges). This electrical double layer (EDL) is formed progressively in time, even from the moment when the two materials get in contact. In the case when the liquid flows, EDL generates an electro kinetic phenomenon, known as flow electrification phenomenon.

In 1924, Stern [11] introduced a model that takes into consideration not only the charge of the ions fixed in the compact double layer (according to the Helmholtz model [12]), but also the charge distributed in the diffuse layer (according to the Gouy-Chapman model [11]). In accordance to this theory, the electrical double layer consists of an immobile layer, where the charge carriers are fixed at the liquid/solid interface, and a diffuse layer, where the charge carriers have a thermal agitation movement [11]. In the diffuse layer, the thermal agitation movement causes the mobile ions to be removed from the fixed charges and thus leads to the formation of a mobile double layer, in which the potential decreases exponentially with the distance from the charged surface. In the absence of the liquid's pouring phenomenon and of the diffusion forces, the electrical migration is canceled, and the distribution of ions is governed by a Boltzmann-type formula, thus the ions from this layer are immobile and are mobbing under the influence of

an electric field or due to the fluid movement0. The physico-chemical processes at the interface generate a new charge transfer compensating the diffuse layer convection and the compact layer remains fixed on the solid surface [13].

The current due to the flow electrification of oil (named "streaming current") appears due to the charge convection coming from the diffuse layer, hence from the oil. This current depends on the electrical double layer's characteristics, the diffuse layer's thickness, the charge density near the solid surface, the electrical double layer development duration; the diffuse layer's thickness being assimilated by the Debye length. The transformer oil's flow electrification is characterized by the value of the electrification currents; the higher is the electrification current, the higher its flow electrification tendency gets [13].

In power transformers, the EDL formed at the mineral oil-pressboard interface has a special importance, and the low electrical conductivity values of both mediums allow an important charge accumulation in the two layers of the interface. The formation and time evolution of EDL depend on the physico-chemical properties of the oil (ageing, impurities content) and pressboard (roughness, porosity) as well as on the oil's temperature [14]. Flow electrification of mineral oil produces local electric discharges which may facilitate the damage and worsen the physico-chemical properties of the power transformer insulation system.

Electrostatic charging tendency and its influence on the degradation of transformer insulation system is a general cause for concern in large power transformers where forced oil circulation is employed using pumps [4, 9].

Considering the future use of vegetable oils in large power transformers with forced oil circulation, it is important to understand the charging tendencies of vegetable oils as compared to mineral oils. Although mineral oils were the target of numerous studies [8-10, 13], vegetable oils are still a novelty and are just being started to be researched. Therefore, this paper presents an experimental study regarding the flow electrification current of a vegetable oil and its comparison with mineral oil using a "spinning disk system". Studies have so far shown that [4] the amount of the charge generated per unit volume of oils (ECT) measured with the set-up named „mini-static tester" is higher for vegetable oil (due to the high moisture content) than for mineral oil. The influence of the oil properties and of the relative velocity of the pressboard (in relation with the oil velocity on the flow electrification current) is mainly analyzed.

2. Experimental set-ups and samples

The flow electrification test was performed using an experimental "spinning disk system" shown in Fig. 2 [15]. Because of the disk, the studied oil is

driven and some electrical charges located at the oil-pressboard interface, move inside the oil, leading to flow electrification. The pressboard disks used have a diameter $d = 100$ mm, thickness $g = 2$ mm and were thermally conditioned at 90°C for 24 hours. Before the introduction inside the measurement cell, the pressboard disk was impregnated with new oil for 24 hours.

The electrification current I_{ss}, measured using an electrometer, appears due to the draining of the electrical charges (of the oil) through the recipient's walls which are grounded.

The experiments were performed on two mineral oil samples, obtained from different producers (noted in this paper as "mineral oil 1" and "mineral oil 2") and a vegetable oil.

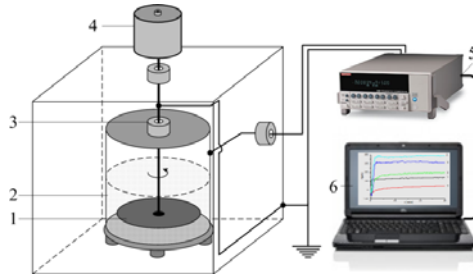

Fig. 2. Spinning disk system for oil electrification current measurement

For the determination of the relative complex permittivity components (ε_r' and ε_r'') and the real part of complex conductivity, a NOVOCONTROL dielectric spectrometer was used. The voltage applied to the samples was 1 V with the electric field frequency in the range of 10^{-3} - 10^3 Hz [16]. The oil resistivity was obtained based on the absorption current $i_a(t)$ measured with a Keithley 6517 electrometer connected with a standard IRLAB CL-1 [17].

3. Electrical charging tendency characterization

In view to characterize the electrical charging tendency of mineral and vegetable oils, the flow electrification current was measured using the previous set-up and samples. In the case of this set-up the flow electrification is the consequence of the rupture of the electrical double layer at the oil - pressboard interface due to the liquid flowing besides the disk. The rotating disk streams the oil in such a way that the oil in the vicinity of the rotating disk has a centrifugal movement which is more vigorous at the periphery of the disk. For low speeds, the oil flow is laminar and the liquid flushes the disk surface and directs the ions to the wall of the oil tank. However, in the case of sufficiently high speeds, the oil presents a turbulent flow characterized by the existence of some vortex at a low

scale related to the geometrical characteristics of the oil tank [18]. Therefore, the interface ions are practically flowed in all oil volume. In such a case, the oil space charge due to the convection of the ions generated at the oil-disk interface is homogenized and it can be considered that the space charge in oil has a quasi uniform repartition. The measured flow electrification current I is due to the leakage of a part of this charge through the metallic tank wall to the ground.

After a time t_{ss} (dependent on the volume and properties of the oil, disk diameter and speed), the oil space charge reaches a limit value and the flow electrification current I reaches the steady state value I_{ss}. The electrostatic charging tendency can be characterized by this steady state current known as electrification current.

Moreover, for $I(t) = I_{ss} =$ ct. the electric charge generated by electrochemical reactions at the oil-pressboard interface in time units is equal to the electric charge which drains through the recipient wall in the same time, respectively is equal with I. Therefore, in well defined experimental conditions, the surface charge density appeared at the oil-pressboard interface in a time unit can be calculated for the different oil types using the following expression:

$$\rho_{ss} = \frac{2I_{ss}}{\pi d^2} \tag{1}$$

where $d = 100$ mm is the disk diameter and I_{ss} is here equal with the value of I measured at $t_{ss} = 60$ minutes from the disk movement start ($I(60)$).

4. Results and Discussions

Figs. 3 - 5 present the time variation curves of the flow electrification currents measured for the mineral oils and vegetable oil samples at different rotation speeds n. It is found that the electrification current values increase with the increasing of the rotation speed. Also, it can be observed that the vegetable oil has a higher flow electrification current than the mineral oils which means that the vegetable oil has a higher charging tendency than the mineral oil.

Table 1

Surface charge density for different oil types

Oil type	Mineral oil 1			Mineral oil 2			Vegetable oil		
Rotation speed [rot/min]	200	400	600	200	400	600	200	400	600
ρ_{ss} [nC/m^2·s]	0.254	0.573	0.95	2.5	6.3	14.3	127	159	222

The values of the surface charge density for different oil types were calculated and presented in table 1. It has been determined that the vegetable oil has the highest surface charge density located at the oil/paper interface compared

to the other two types of mineral oil. The difference between vegetable and mineral oil's surface charge density is significant (it can be 200 times higher in the case of vegetable oil).
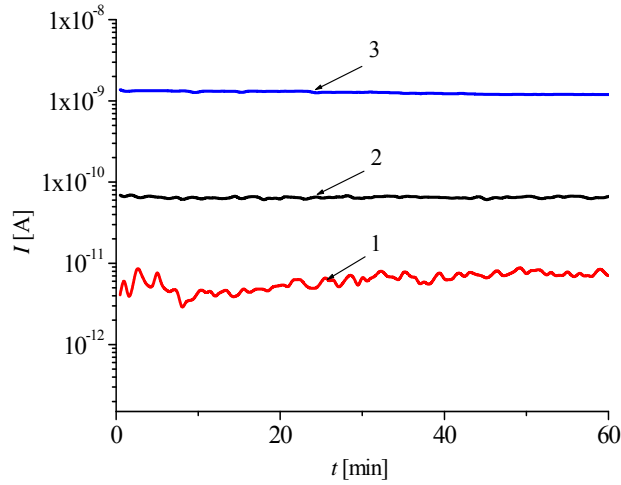

Fig. 3. Time variation of the flow electrification current for mineral oil 1 (1), mineral oil 2 (2) and vegetable oil (3) for $n = 200$ rot/min.

Figs. 6 and 7 present the variation of the real part of relative permittivity and of the real part of electrical conductivity with the frequency. It can be seen that, due to its polar nature, vegetable oil's ε_r' and σ' has higher values. Considering that the vegetable oil has higher hygroscopicity than mineral oil, and the fact that the water molecule is polar, this could have a big influence on the relative permittivity value of the oil.
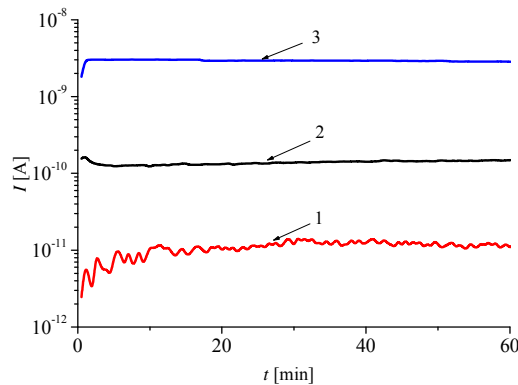

Fig. 4. Time variation of the flow electrification current for mineral oil 1 (1),

mineral oil 2 (2) and vegetable oil (3) for n = 400 rot/min.
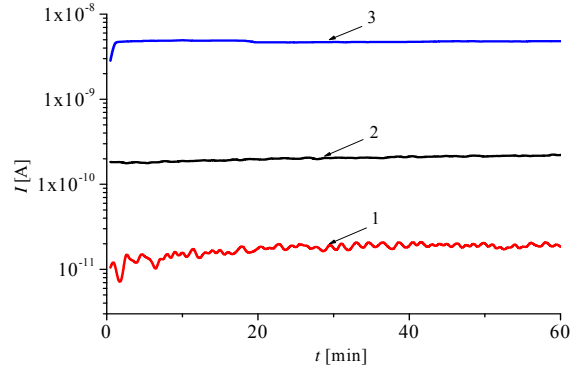

Fig. 5. The time variation of the flow electrification current for mineral oil 1 (1),
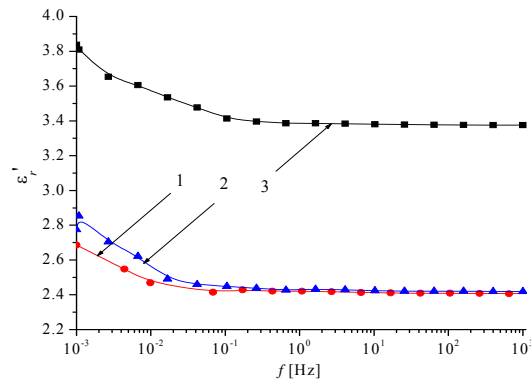mineral oil 2 (2) and vegetable oil (3) for n = 600 rot/min.

Fig. 6. Variation of the real permittivity component ε_r' with frequency f,
for mineral oil 1 (1), mineral oil 2 (2), vegetable oil (3).

Fig. 8 presents the volume resistivity variation with respect to time for mineral and vegetable oil samples. It can be seen that vegetable oil has lower resistivity values than the mineral oil.

The results of the real part of the relative permittivity (measured at 50 Hz respectively 1m Hz), real part of conductivity and volume resistivity determined for vegetable and mineral oil are given in Table 2. It can be seen that the values of vegetable oil's complex relative permittivity components are higher than mineral oil's. Further, the volume resistivity of vegetable oil is 10^{11} Ω·m, a value lower than the value obtained for mineral oil, i.e. 10^{13} Ω·m. It can be said that there is a correlation between the lower values of the vegetable oil's resistivity, its higher values of relative permittivity and its higher electrification tendency.
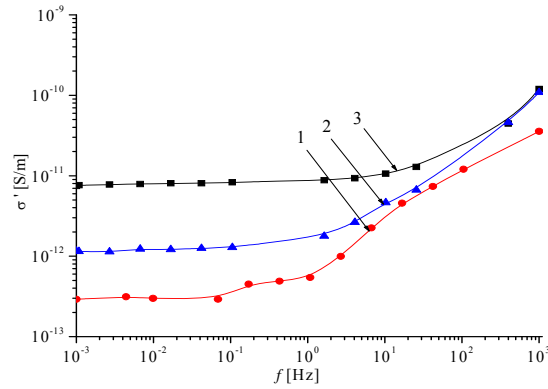
Fig. 7. The variation of real part of electrical conductivity with frequency f,
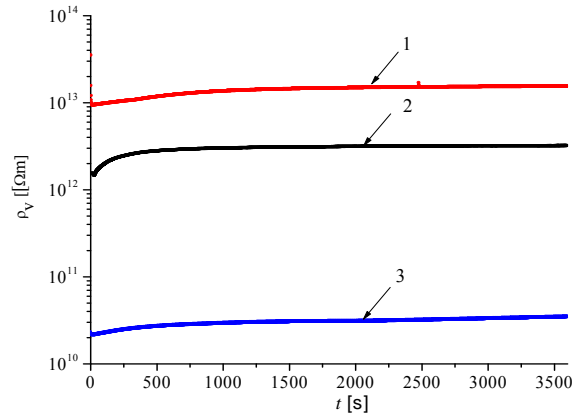for mineral oil 1 (1), mineral oil 2 (2), vegetable oil (3).

Fig. 8 The time variation of the volume resistivity for mineral oil 1 (1),
mineral oil 2 (2), vegetable oil (3).

Considering all the above results, the higher values of the real part of relative permittivity and flow electrification current of the vegetable oil are most likely due to the presence of polar molecules in the oil, including those of the water contained in the oil, since the inherent moisture retention levels of vegetable oils are higher as compared to mineral oils [4]. From this point of view it must be kept in mind that at room temperature, the saturation limits of natural ester and mineral oil are very different; about 3000 mg/Kg for natural ester and 60 mg/Kg for mineral oil [19].

Table 2

The flow electrification current and the electric properties of transformer oils

Property	Values		
	Vegetable oil	Mineral	Mineral

		oil 1	oil 2
ε_r' (f = 50Hz)	3.4	2.41	2.42
ε_r' (f = 1 mHz)	3.81	2.7	2.82
σ' [S/m] (f = 50Hz)	$3 \cdot 10^{-11}$	$9 \cdot 10^{-12}$	10^{-11}
ρ_v [Ω-m]	$6 \cdot 10^{10}$	$2 \cdot 10^{13}$	$6 \cdot 10^{12}$
I_{ss} [A] (200rpm)	$2 \cdot 10^{-9}$	10^{-11}	$8 \cdot 10^{-11}$
I_{ss} [A] (600rpm)	$7 \cdot 10^{-9}$	$3 \cdot 10^{-11}$	$2 \cdot 10^{-10}$

In order to better observe the changes in ε_r**,** the values measured at a frequency of 1 mHz were chosen because at low frequencies the polarization phenomenon is much more obvious, due to the easier orientation of the dipoles after the electric field.

The correlation between the oil's main dielectric properties and the flow electrification current can be highlighted by an empirical relation used to calculate I_{ss} (measured at 200 rpm) as a function of the real part of the relative permittivity (measured at f = 1mHz):

$$I_{ss} = a + b \cdot \varepsilon_r' + c \cdot \varepsilon_r'^2 \text{ ,} \tag{2}$$

where a = $7.73684 \cdot 10^{-9}$ A, b = - $6.16032 \cdot 10^{-9}$ A and c = $1.22168 \cdot 10^{-9}$ A are constants.

Table 3

Empirical relation between the flow electrification current and the real part of relative permittivity

Dielectric property	Vegetable oil	Mineral oil 1	Mineral oil 2
ε_r' (f = 1mHz)	3.81	2.7	2.82
$I_{ss\ (measured)}$ [A]	$2 \cdot 10^{-9}$	10^{-11}	$8 \cdot 10^{-11}$
$I_{ss\ (calculated)}$ [A]	$2 \cdot 10^{-9}$	$1.002 \cdot 10^{-11}$	$8.003 \cdot 10^{-11}$

It can be seen that the calculated values of I_{ss} are almost equal to the measured ones.

5. Conclusions

The present paper brings forward an experimental study which highlights the existing links between the main electrical properties of mineral and vegetable transformer oil and the flow electrification phenomenon.

The experiments conclude that the complex permittivity components and the electrification currents of the vegetable oil are higher than those of the mineral oils. It can also be noticed that the vegetable oil's volume resistivity is lower than that of mineral oil. Also, an empirical relation used to calculate I_{ss} (measured at 200 rpm) as a function of the real part of the relative permittivity (measured at

$f = 1$ mHz) was determined. There was no significant difference between the measured value of the flow electrification current and the calculated one.

In future work, the influence of accelerated thermal stresses on the electrification phenomenon for mineral and vegetable oil will be analyzed in order to highlight the existing links between the oil's real part of relative permittivity, real part of conductivity, volume resistivity and its electrification tendency.

Acknowledgment

R E F E R E N C E S

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