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Impact of various stresses on the streaming electrification of transformer oil

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ABSTRACT

In this contribution the influence of various stresses and their combined impact on the electrostatic charging tendency of oil is studied. Various physicochemical properties were measured according to ASTM Standards to detect changes in oil quality. A free radical reagent, 2.2 diphenyl-1-picrylhydrazyl (DPPH), was added to oil before and after the application of stresses to determine free radical concentration. The results obtained show that the application of stresses contributes to an increase in the electrification current. These results also demonstrate that electrification current is affected by the quantity of the free radicals.

1. Introduction

The role of insulation is paramount importance, in the sense that it is one of the fundamental conditions for the reliable operation of power equipment. Insulating materials design/selection is one of the most important problem engineers have to face. This is due to wide variety of available insulation (oil, air, vacuum, ceramic, etc...). Moreover, insulating materials span all three forms of matter (solid, liquid and gas), with sometimes a single form involved but often a combination of forms, such as the solid/liquid or the solid/gas forms.

Composite liquid/paper insulation is used in power transformer. Insulating liquid in transformer is mainly of mineral origin, but may be of synthetic and vegetable origin [1]. The most widely used insulation systems for nearly a century are petroleum-based oil, (the so-called transformer oil) combined with solid insulation. The solid insulation materials commonly used as wrapping (e.g., turn insulation, cable wraps) and spacers (e.g., layer insulation) are cellulosic papers and boards made with special care from wood pulps [2]. These papers, pressed boards (the so-called pressboards), and wooden parts show modest dielectric performance due to their porous structure. Their dielectric strength is predominantly conditioned by gaseous ionization within the air inclusions. They are therefore adequately impregnated with transformer oil to eliminate air and increase their resistance to electrical breakdown.

When a liquid comes in contact with a solid wall, the complex liquid–solid polarizes under the effect of a physicochemical phenomenon at the interface; this process leads to the generation of charges within solid/insulating liquid interfaces. The system can be considered in equilibrium when there is no more charge transfer at the interface (no current flowing at the interface): the chemical reaction is stopped or considered stationary, offset by leaks to ground via the interface. Any motion of the liquid affects this dynamic equilibrium condition. The lack or smaller amount of counter charges in the liquid introduces an imbalance for which

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compensation is made by new reactions at the interface generating the streaming/electrification current. The physicochemical processes at the interface generates new charges transfer, compensating the convective transport of the diffuse layer, the generated current is also equal to the currents created by the leak and transient accumulation of charges at the interface, the compact layer remaining integral with the interface [3–5]. It is generally accepted that the transport of charges, present in the diffuse layer is responsible for the electrical double layer (EDL) “rupture” [4].

The streaming current is due to the convection of charge from the layer diffuses into the liquid. It depends on the properties of the double layer: thickness, density of space charge at the interface, and the duration of the double layer.

The thickness of the diffuse layer is generally equated with the Debye length [4].

Streaming/flow electrification in power transformers has been studied for decades, since the charge generation phenomenon was suspected to be responsible for power transformer failures [6].

In the case of the mineral-oil impregnated pressboard and papers, it is observed that the pressboard generally holds a negative charge, while the oils hold a positive charge [4–28]. The oil does not remain charged for a long time because its flow makes it possible for the positive charges to be released, once they contact any metal part connected to the mass (tank). On the other hand, the pressboard retains its negative charges. The charges accumulated at the pressboard–oil interface can lead to high potentials and initiate partial discharges [5].

Many studies reported in the literature made it possible to determine the main factors that influence static electrification [4–28]. Among these factors the purity of oil was recognized as an important one. At the same time, several devices were being developed to study the phenomenon. Different facilities and protocols have been developed for studying the electrostatic charging tendency (ECT) in a spinning disk system [6,7], Couette charger [8,9] or in the Westinghouse protocol [10]. All these measurements analyzed hazards according to the streamed charges, commonly called “streaming current”. At the University of Poitiers, an original sensor was developed to measure the quantity of charge that accumulates in well-insulated pressboard [11–15].

Under normal operating conditions, transformer oil is degraded due to various stresses, including electrical, chemical, and thermal ones. The degradation by-products or decay products in the insulating oil are composed of a variety of compounds, such as peroxides, aldehydes, ketones and organic acids. Each one of them is partially adsorbed on the large surface of the paper insulation. This article contains experimental results of the electrostatic charging tendency (ECT) of mineral-based oil submitted to the following stresses: electrical stress, local thermal overheating and a combination of both stresses in a spinning disk system. The results are correlated with the concentration of dissolved decay products (DDP) and free radicals content in the fluid samples. The influence of the type and thickness of papers on the ECT of oil is also investigated.

2. Experimental procedure

The investigations were performed using a spinning disk system designed in our laboratory, in which the disk is covered on both sides with cellulose or aramid paper [20–25]. This system has been adopted by CIGRE (Conférence des Grands Réseaux Électrique, Paris, France) for international comparative measurements of both insulating liquid and solid transformer materials (CIGRE Paper [16,17]) and is used relatively often in streaming electrification studies [6,7,18–27].

A disk having a diameter of 40 mm and a thickness of 5 mm was used in these investigations. The spinning disk system and the electrometer were placed in a Faraday cage (Fig. 1). The rotating disk was driven by a proportional-integral (PI) based speed controlled DC motor. The rotating velocity of the disk was varied between 100 and 600 rpm. The container as well as the rotating disk was made of aluminum. The temperature of oil was set and controlled within the range of 20 ± 0.1 °C using a heating system. The electrification currents and the rotation speed measured using an encoder, were simultaneously recorded via a data acquisition Excelinx system developed by Keitley. The data were stored as Excel files to allow further analyses using other software applications. The static electrification current (leakage current) created by the charge concentration gradient was measured with a programmable electrometer (Keitley 6514) inserted between the tank and the ground.

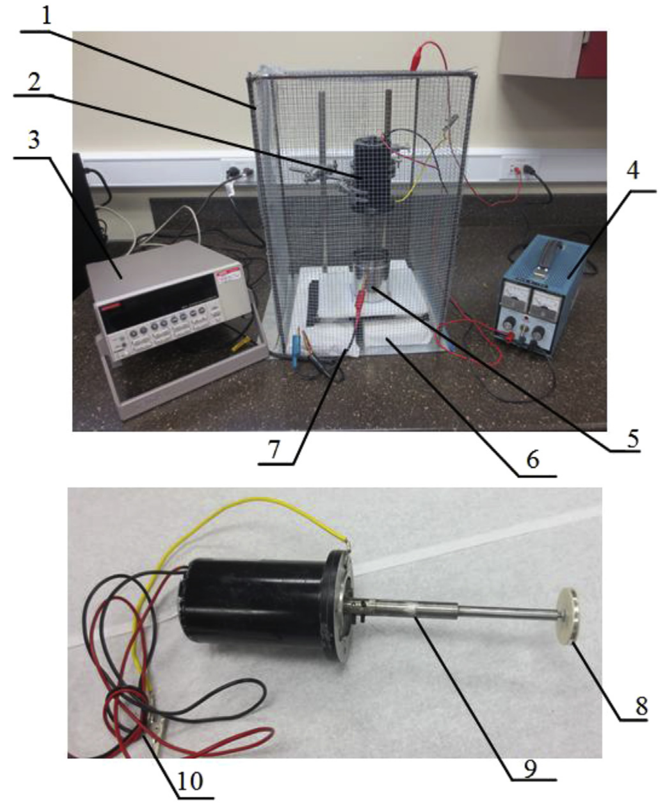


Fig. 1. Diagram of the system with a spinning disk for studying the electrification of insulating liquids: (1) Faraday cage; (2) DC motor; (3) Electrometer; (4) DC power supply; (5) measuring container containing oil; (6) insulator; (7) coaxial cable; (8) disk (9) rotating mandrel (10) connecting wire.

Due to centrifugal force, the charges created by the rotating motion of the disk in oil are drained toward the tank wall, where they are collected. The streaming current was measured as leakage current (in pA), from the container to the ground using an electrometer inserted between the tank and the ground.

The electrometer, based on the National Semiconductor LMC6001 BiFET op-amp, had an input resistance of 10^{15} Ω and an input bias current no greater than 25 fA. The 1000 MΩ feedback resistor made it possible to take measurements as low as ±5nA. The 500 kΩ input resistor limited the input current to safe levels in cases of significant electrostatic potential on the electrometer input. Two different papers were used to cover the rotating disk: (i) cellulose having a thickness of 1 mm and 3 mm, and (ii) a 1 mm thick Aramid Paper. These paper samples were vacuum dried in an oven at 100 °C for 48 h, and then impregnated with dehydrated, degasified naphthenic type based inhibited oil.

Table 1
Some technical data concerning mineral oil.

ASTM tests	Mineral oil
Dissipation factor (%)	
@ 100 °C, D 924	<0.1
Breakdown voltage (kV)	
D 877	>40
D 1816 (0.08″gap)	>50
Gassing tendency (μL/min), D 2300B	negative
Water content (ppm), D 1533	<20
Interfacial Tension (dynes/cm @ 25 °C), D 971	48
Total Acid Number (mg KOH/g), D 974	<0.01
Viscosity (mm^2/s), D 445	
40 °C	7.5
100 °C	1.9
−40 °C	2100
0 °C	45
Color, D 1500	<0.5
Flash point (°C), D 92	150
Pour point (°C), D 97	−63

The electrostatic charging tendency (ECT) was studied for a naphthenic-based mineral oil. Table 1 summarizes some of the main properties of mineral oil.

For each sample of oil, the electrification current was recorded for different rotational velocities. At each velocity, the currents were recorded with a sampling rate of 195 samples/min. The mean value of the electrification current was calculated and used for further analysis. In addition to static electrification, the dielectric properties were also assessed, i.e. the moisture content by Karl Fisher titration [28], turbidity in oil by a ratio-turbidimeter [29], the interfacial tension (IFT) [30] and the dissolved decay products (DDP) by UV/Vis spectrophotometer [31]. Also, the relative quantity of free radicals contained in new oil and after the application of various stresses was assessed using a method of spectrophotometry UV-VIS.

3. Discussions and results

The mineral oil sample was submitted to various stresses:

- Electrical discharge according to ASTM D 6180 is referred to as *Stress 1*. A Merell-based test cell type, defined in the ASTM Test Method D 6180, was used (Fig. 2). The free electrons are generated by a cylindrical copper electrode 15 mm (0.6 inches) in diameter and 10 mm long sealed in a 500 ml Erlenmeyer glass. The electrode is placed in the center of the discharge cell and suspended above the oil.

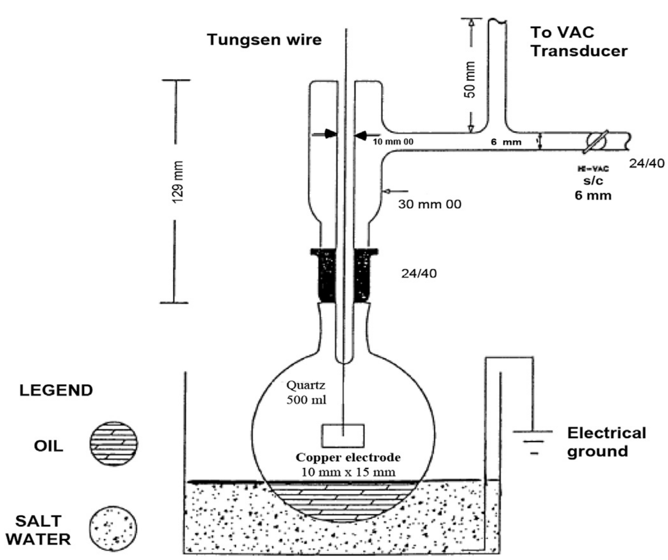


Fig. 2. Discharge cell according to ASTM D 6180.

The distance between the central electrode and the surface of oil is approximately 25.4 mm (1 inch). Before applying the voltage, the discharge cell was vacuumed down to 1 Torr (133 Pa). After vacuum degassing, the oil sample was subjected to high voltage discharge of 10 kV during 5 h. After measuring five times, the pressure increases inside the discharge cell to assess the quantity of gasses evolved.

Electrical breakdown according to ASTM D 877 [32] is referred to as *Stress 2*. This type of breakdown does not provide a long burning arc, but more like a spark in the oil. 50 breakdowns were initiated in the oil. The level of voltage corresponds to the minimum threshold of the oil's degradation [33] (Fig. 3).

- Local overheating is referred to as *Stress 3*: a laboratory designed setup [34] was used to simulate a local hot spot in the oil samples. The setup consists of a Borosilicate-glass vessel and a Teflon cover with clamps to hold the heating wire. The heating wire is made of constantan due to its stable resistivity in a wide range of temperatures. The local overheating was applied for 30 min. The temperature, measured with a NiCrNi-temperature sensor, reached approximately 250 °C. The heating current is supplied by a high current transformer, while the temperature of the wire was regulated by an ampere meter connected to the secondary circuits. This test setup allows the local controlled heating of the liquid beyond 500 °C [34] (Fig. 4).
- The oil samples were also submitted to combination of these stresses as illustrated in Table 3.

Tables 2 and 3 report some of the physicochemical properties of oil and paper which are the moisture content [28], the Interfacial tension (IFT) [30], Turbidity [29] and Dissolved Decay Products (DDP) [31]. These properties were measured before and after the application of stress.

The values reported in Table 2 indicate that this oil is of poor quality and contains a considerable quantity of residual polar compounds or molecules, unstable hydrocarbons and volatile molecules.

As long as chemical bonds inside the hydrocarbon chains are not broken, the generation of decay products is impeded. The increase in the temperature of oil may provide energy capable of splitting a covalent bond. Moisture (which is considered the enemy number one of solid insulation); copper/copper alloys in aluminum windings and iron (which are primary transformer components); and oxygen act as aging catalysts while heat, aging by-products, dirt, vibration, electrical stress, and so on, accelerate the process.

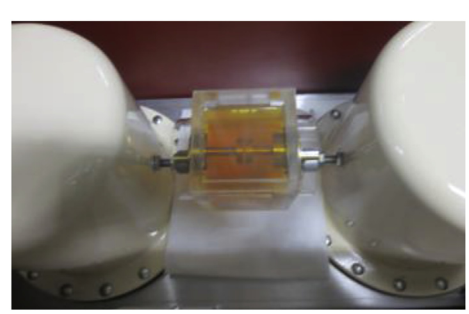
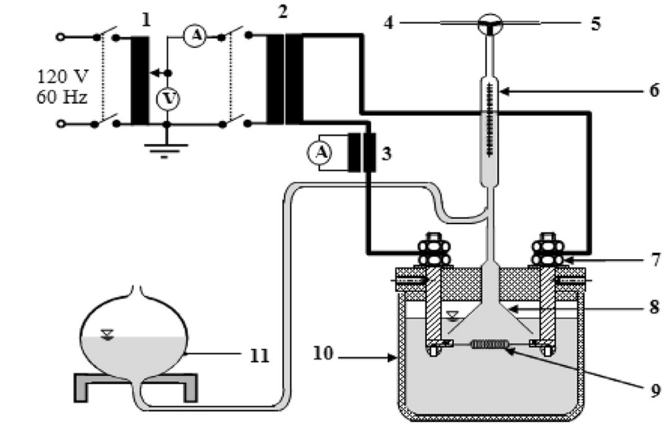


Fig. 3. The experimental cell allowing the generation of arcs in oil to ASTM 877.



1.	Auto-transformer	7.	Clamps
2.	Current transformer	8.	Funnel
3.	Measuring transformer	9.	Heating elements
4.	Sampling for gas	10.	Test vessel
5.	Sampling for gas	11.	Equalising vessel
6.	Measuring pipette		

Fig. 4. Prototype used for local overheating of the insulating fluid samples.

Electrical stress together with heat and moisture, in the presence of oxygen, oxidises the oil producing free radicals, acids, and sludge that are deleterious to the transformer [35]. Free radicals may be generated by thermal decomposition, electrical discharge, electrolysis at an electrode, mechanical damage, chemical reactions, and high energy radiation and are thus implicated in the ageing process [35].

When weak bonds split, free radicals are formed. These radicals are highly unstable and react quickly with other compounds, trying to capture the needed electron to gain stability. Broken molecules and “knocked-out” hydrogen atoms are free radicals and hence paramagnetic. Through secondary chemical reactions, the small fragments of broken molecules usually generate a gas that dissolves in the oil without modifying the one phase system. The collision of two large free radicals leads to the formation of large colloidal compounds having a molecular weight between 500 and 600 (sludge that is a solid phase) that are no longer soluble in the oil. When two large free radicals couple their unpaired electrons to generate a similar insoluble hydrocarbon without oxygen in the middle, the decay product formed has the generic name of x-wax. The increase in free radical concentration increases random chemical reactions between free radicals. Thus, soluble and insoluble oil-borne decay products are the outcome. As a result, the products of dissolved decomposition such as DDP (peroxides, aldehydes, ketones and organic acids, alcohols, anhydride of acid, metal soap) and turbidity (sludge of asphalts, soap sludge, carbon sludge…) are likely to increase while the interfacial tension (IFT) decreases (Table 3).

When hydrocarbon molecules (mineral oil) are subjected to the electric stress, they tend to break up into free radicals and to precipitate in the form of sludge or waxes [35]. The increase in turbidity indicates the formation of colloidal suspensions. The presence of colloidal suspensions affects the oil's ability as an insulant and may affect the cooling efficiency of the transformer. This reduction in oil rigidity of is also shown by the high moisture values.

The relative free radical content of petroleum-based insulating oils origin was determined using a UV-VIS Spectrophotometric method. The DPPH assay of the essential oil was carried out as previously described [35–37]. A reactive free radical reagent, 2,2-diphenyl-1-picrylhydrazyl (DPPH), is added to a solution of toluene and oil whose free radical concentration is to be determined. The rate that the DPPH disappears is directly proportional to the relative free radical content at a particular instant of time. Solutions of DPPH, even at a concentration of 10^{-5} M, are blue-violet in color. The more radicals are present in the oil, the faster it reaches zero absorbance. The scavenging activity of DPPH can be represented by the following chemical reactions, where AH denotes an anti-oxidant and R, a free radical:

$$\mathrm{DPPH} + \mathrm{AH} \rightarrow \mathrm{DPPH} - \mathrm{H} + \mathrm{A} \tag{1}$$

$$\mathrm{DPPH} + \mathrm{R} \rightarrow \mathrm{DPPH} - \mathrm{R} \tag{2}$$

The reaction mixture was vortexed thoroughly, left in the dark at 25 °C for 30 min and measured at 520 nm.

The absorbance curve of the area was performed for every sweep. The ability of the oil sample to scavenge DPPH radical was calculated as % inhibition by the following equation [36]:

$$\%\,\mathrm{Inhibition} = \frac{\mathrm{Abs\ Control} - \mathrm{Abs\ Sample}}{\mathrm{Abs\ Control}} \times 100 \tag{3}$$

where Abs control is the absorbance of the DPPH radical + toluene; Abs sample is the absorbance of DPPH radical + oil sample. The

Table 2
Some physicochemical properties of mineral oil and paper at 20 °C before the application of the stresses.

	Water content (ppm)	Turbidity (NTU)	DDP (u.a.)	IFT dynes/cm, T = 22 °C)
Mineral oil	2.4	0.728	3.38	34
Aramid paper	0.1%	–	–	–
Cellulose	0.2%	–	–	–

Table 3
Some physicochemical properties of mineral oil at 20 °C after the application of the stress(es).

	Water content (ppm)	Turbidity (NTU)	DDP (u.a.)	IFT (dynes/cm)
Stress 2	17.2	1.8	8.73	32
Stress 1	23.7	2.14	12.79	31
Stress 3	28.3	2.53	45.39	29.5
Stress 1 + Stress 2	27.8	2.28	45.79	28.5
Stress 3 + Stress 1	31.7	2.78	59.27	26
Stress 3 + Stress 2	29.7	2.65	46.10	27.5
Stress 3 + Stress 2 + Stress 1	34.3	3.5	68.30	26

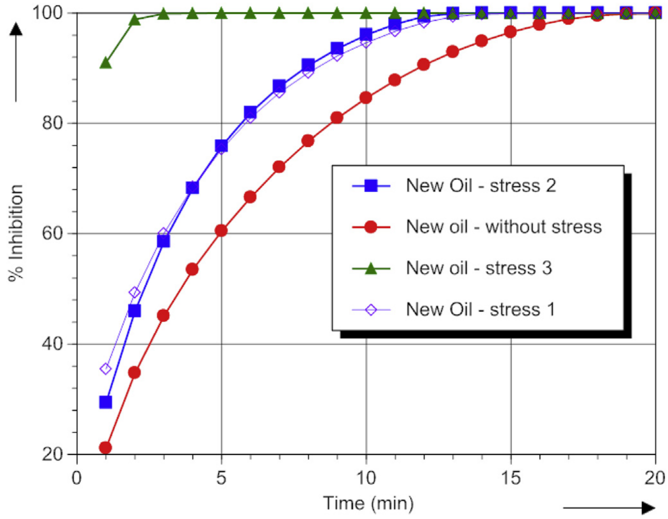


Fig. 5. Antioxidant activity of unused and used (after the application of various stresses) oil samples as a function of time with a DPPH reference solution at a 0.01% concentration.

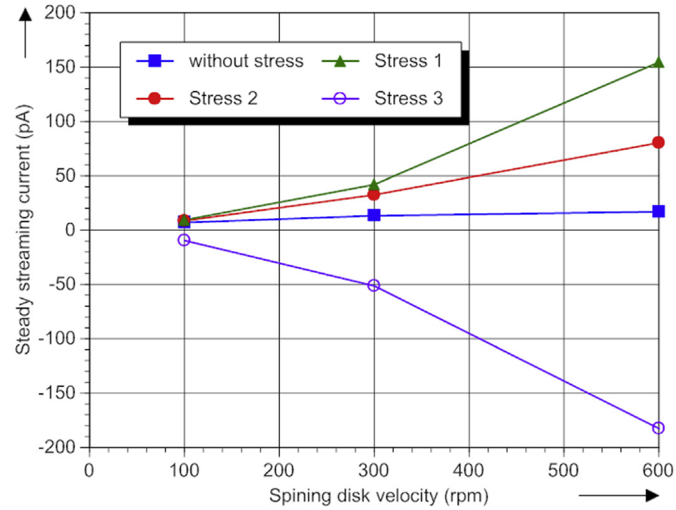


Fig. 7. Average streaming electrification current of mineral oil (after the application of stresses) as function of the spinning disk velocity. The measurements were performed at 20 °C with a disk diameter of 4 cm covered with 1 mm thick Aramid paper.

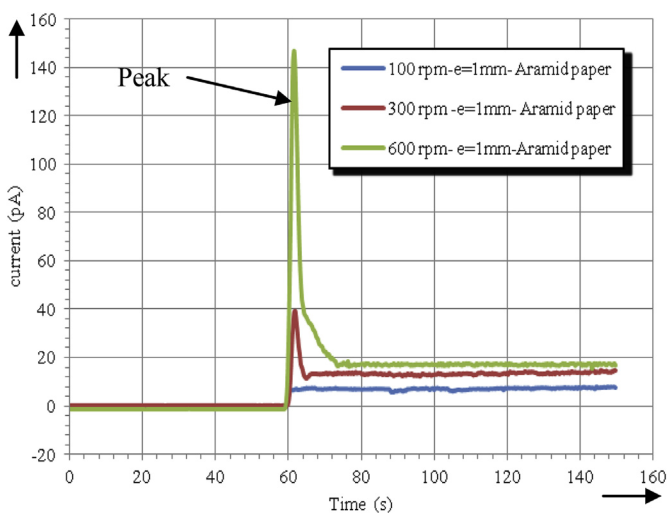


Fig. 6. Temporal evolution of the streaming electrification current (disk diameters 4 cm with 1 mm thick Aramid) for the mineral oil before application of stresses (without stresses). The measurements were performed at 20 °C. The spinning disk velocity acted as a parameter.

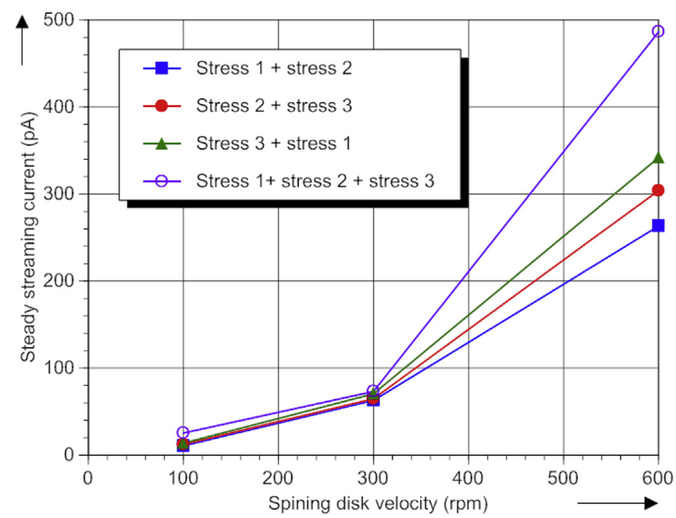


Fig. 8. Average value of the streaming electrification current (disk diameters 4 cm covered with 1 mm thick Aramid paper) versus the spinning disk velocity, for mineral oil (after combination of stresses). The measurements were performed at 20 °C.

results of these measures performed every 60 s for a total duration of 20 min, are summarized in Fig. 5.

It can be seen that the inhibition increases with time elapsed. The amount of free radicals increases in the new oil sample after stresses applications. Thermal stress yielded a higher amount of free radicals. Oil thermally stressed demonstrated stronger inhibitions (Fig. 2). New oil had lower activity than the stressed oils.

a. Influence of stresses applied and spinning disc velocity

Out of Fig. 6, it can be observed that the peak value of the streaming electrification current increases with velocity of the disk to reach saturation. The accumulation of charges is important at higher speeds (600 rpm). The variation of current for different speeds is practically weak because our oil sample did not contain many impurities; measurements evidenced by data reported in Table 2 confirm this result. The sign of the current is positive for all speeds. The currents measured during the studies carried out with ECT device and the loop of flow of the LEA [5] clearly confirmed this observation.

Figs. 7 and 8 represent the average streaming electrification current as a function of the spinning disk velocity for different stresses (electric and thermal), respectively, and the combination of these stresses.

The streaming electrification current increases after stress application. This increase is much higher after the application of thermal stresses for all the spinning disk velocities. The injection of free electrons (e^-) in oil (Stress 1) breaks the chemical bonds between the hydrocarbon chains; after this rupture, the buildup of decomposition by-products is possible [35–41]. These products accelerate the aging of oil and paper and increase the viscosity of oil. The electrostatic charging tendency (ECT) increases along with the escalation of the liquid's viscosity. The decomposition of the hydrocarbon chains produces a number of important free radicals that affect the electrification current.

The streaming electrification current is significantly higher after the application of Stress 1. This is mainly because in the stress 1, the

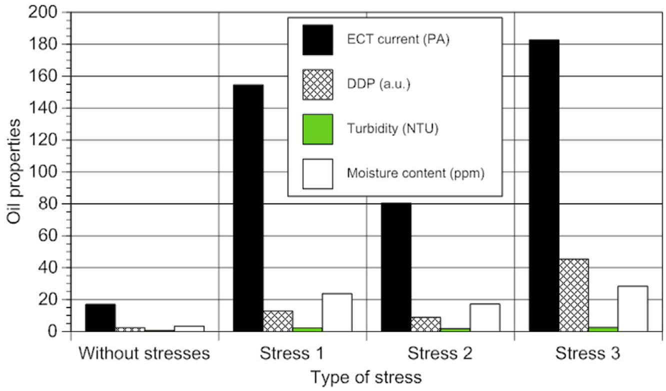


Fig. 9. Relationship between mineral oil properties and the streaming electrification current (disk diameters 4 cm covered with 1 mm thick Aramid paper). The measurements were performed at 20 °C with a spinning disk rotating speed at 600 rpm.

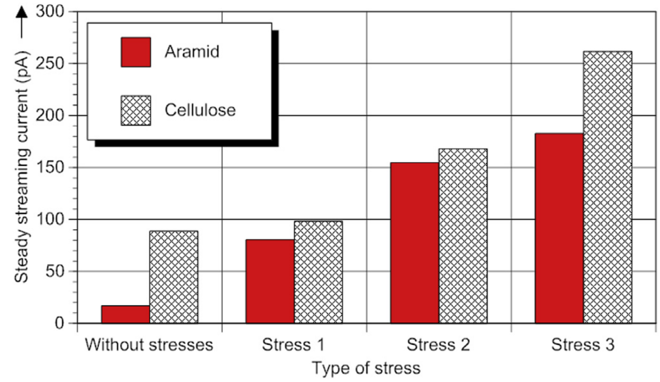


Fig. 11. Average value of the streaming electrification current (disk diameters 4 cm covered with Aramid paper or Cellulose) for the mineral oil before and after application of stresses. The measurements were performed at 20 °C, with a spinning disk rotating speed at 600 rpm.

oil sample was stressed during 5 h, compared to the 50 breakdown tests caused in oil (Stress 2). Heat produced by the magnetic boundary-layer is another factor that contributes to the degradation process [39], since high temperatures activate chemical reactions that precede the formation of decay products and increase the mobility of charge carriers and free radicals [35]. The temperature directly affects viscosity values.

Application of thermal stress caused inversions of the charge polarity of the usually measured current. This phenomenon of sign inversion was also observed after the addition of certain additives in oil [5].

From Fig. 8, it can be observed that electrification currents are much higher after the application of combined stresses. This phenomenon can be traced to the large number of broken hydrocarbon bonds after the application of stresses that cause severe degradation. As expected from the data reported in Table 3, the ECT increases with applied stress.

Fig. 9 summarizes the variation of the electrification current and aging indexes, such as DDP, turbidity, IFT and water content. These properties were measured after the application of stresses according to ASTM standards.

The ECT increases with increasing DDP, Turbidity and moisture content. The decomposition by-products worsen the quality of oil and paper and increase the leakage current. The relation between the products of decomposition and the streaming electrification current has been studied over the past decade [21,40].

b. Influence of the material covering the disk

A cellulose-based paper and a poly-aramid-based synthetic insulation were both considered. Poly-aramid-based synthetic insulation, with a trade name Aramid®, is more expensive than cellulose. Aramid is used selectively in high temperature demanding applications, for example in traction transformers.

Figs, 10 and 11 show the influence of the oil/paper interface on the electrification phenomena. The electrification current increases after the application of stresses. From Figs. 10 and 11, it can be observed that the electrification current increases after the application of stresses. The streaming electrification generated at the interface between the spinning disk and the flowing oil, is influenced by the physicochemical composition of material used to cover the disk. This observation stressed that the chemical composition of papers plays a significant role in the ECT of oil. The porosity of the papers (diameter, length, number of pores) may also play an important role [21,42]. Generally speaking, the ECT is higher

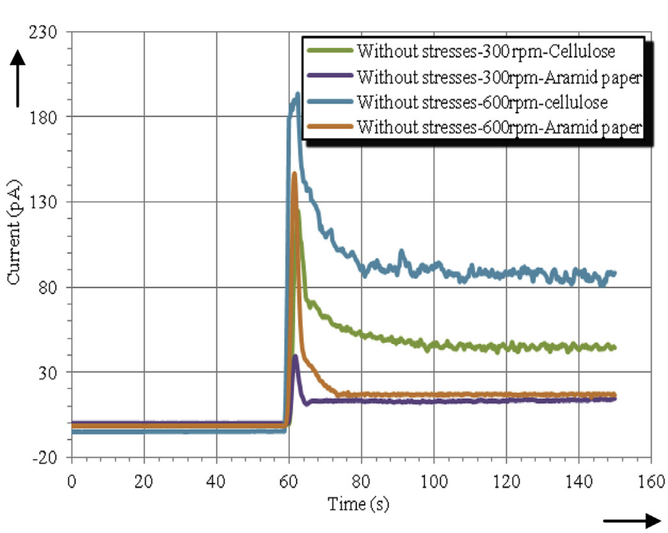


Fig. 10. Temporal evolution of the streaming electrification current (disk diameters 4 cm with Aramid paper or Cellulose) for the mineral oil before the application of stresses (without stresses). The measurements were performed at 20 °C.

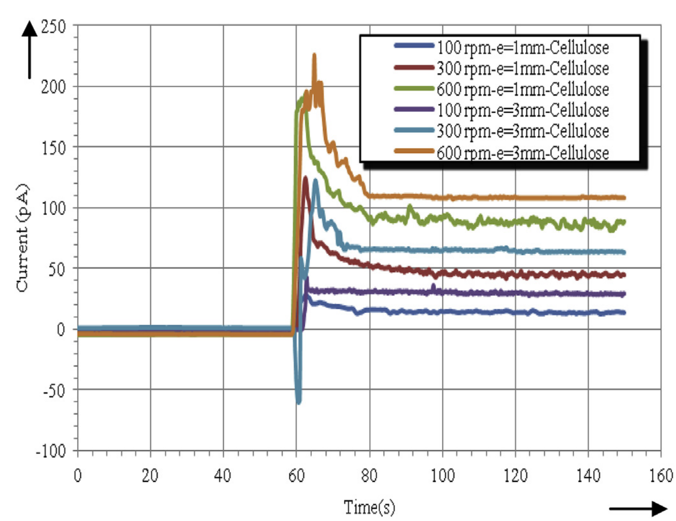


Fig. 12. Temporal evolution of the streaming electrification current (disk diameters 4 cm with Cellulose) for the mineral oil before application of stresses (without stresses). The measurements were performed at 20 °C. The spinning disk velocity acted as a parameter.

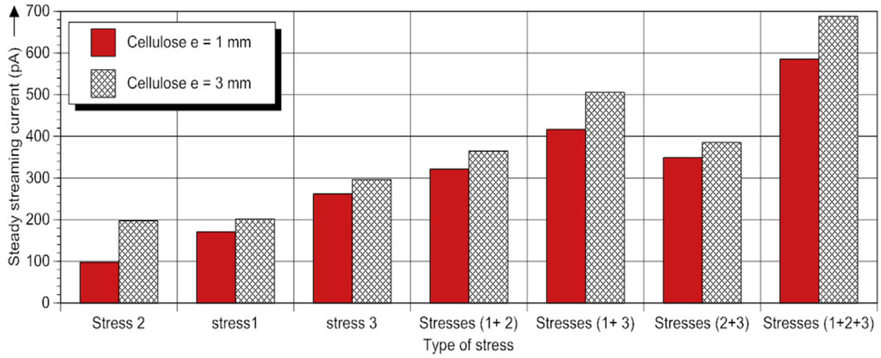


Fig. 13. Average value of the streaming electrification current (disk diameters 4 cm covered with Cellulose) for mineral oil after application of stresses. The measurements were performed at 20 °C, with a spinning disk rotating speed at 600 rpm.

when oil is paired with cellulose-based paper. For un-stressed papers, Aramid is less affected by the streaming electrification. Chemically, the smoother surface and chemical structure of Aramid are factors that probably help limit the streaming electrification phenomenon [43]. Unlike cellulose paper, its thermal stability allows reducing the ECT in the oil.

c. Influence thickness of paper

From Figs. 10 and 11, it was observed that cellulose depicted higher tendency to charges generation. These tests were therefore, performed with cellulose. The variation of the electrification current with the thickness (e) of paper is represented by Figs. 12 and 13.

The results portrayed in these Figs. 12 and 13 show that the electrification current increases with the thickness of paper. Likewise, the electrostatic charging tendency (ECT) is affected by the thickness of the solid insulation as reported in the literature [43].

By increasing the thickness of dielectric material, the accumulation of charges increases at the interface of oils/paper. It is important to note that the higher the charge density at the interface the higher the streaming electrification current is [27].

4. Conclusions

In this contribution, the experimental investigations onto the electrostatic electrification for unused mineral oil under the impact of electric and thermal stresses were carried out in a disk spinning system. The results obtained show that:

- the spinning speed has a direct impact on the electrostatic charging tendency (ECT).
- ECT is influenced by the roughness and the porosity of paper; the manufacturers of paper may find it beneficial for the design/manufacture of materials with the flow of oil in mind.
- ECT is affected by the relative quantity of the free radicals.
- Under controlled laboratory conditions, it was shown that incipient electrical and/or thermal failures in the transformer increase the electrostatic charging tendency (ECT). This may initiate partial discharge and subsequent short-circuit with dramatic consequences for the utilities and customers.

These results emphasize the need for diligently monitoring the transformer oils during service. Since the condition of oil can be a decisive factor, which determines the life span of the transformer, it must therefore be kept in pristine condition. The results indicate that Dissolved Decay Products (DDP), turbidity, interfacial tension (IFT) and the relative amount of free radicals values can be possibly used as an effective index for insulating oil degradation assessment.

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