Effect of TiO_2 nanoparticles on the performance of a natural ester dielectric fluid

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***Abstract*—Mineral oil has been frequently used in most of high voltage transformers. However, this oil has started to be replaced by vegetable oils. Additionally, different authors have found that mineral oil-based nanofluids have a potential in improving insulating properties of transformer oil. In order to improve the characteristics of a commercial vegetal oil, this work has used TiO_2 nanoparticles to obtain a nanofluid whose ageing behavior at 150°C for 300 hours has been studied.**

Keywords—TiO_2 nanoparticles; vegetal oil; nanofluid; thermal aging; Kraft paper

I. Introduction

Transformers are a critical part of the electricity generation and distribution network. In transformers, the insulating system most widely used is based on the combination of a solid and a liquid insulation. The degradation of this system as a consequence of ageing determines the transformer's life [1]. During last decades vegetable insulation oils based on natural ester oils, have been introduced as substitutes for mineral oil for their use in power transformers. The main reasons for that are these oils are less flammable and quite more biodegradable than mineral oil [2]. These new liquids should meet several requirements such as high dielectric strength and heat transfer capability as well as, stability and compatibility with other transformer materials [3].

Recently, transformer oil-based nanofluids have attracted a great deal of attention because well-dispersed nanoparticles are capable of enhancing dielectric and cooling performances of the oil [4-6]. There are several papers which have analyzed the effect of different nanoparticles (conductive, semi conductive and insulating) on dielectric properties of mineral oils [6]. Semi conductive TiO_2 nanoparticles is an example of particles used to produce nanofluids. For example, Mansour et al. prepared oil-based nanofluids with TiO_2 nanoparticles and mineral oil [7-9]. These authors concluded that the addition of different TiO_2 concentrations produced different increases in the breakdown strength of nanofluid samples. Similar results with TiO_2 nanoparticles were obtained by Yue-fan et al. [10, 11] and Hanai et al. [12]. Other papers have evaluated if the positive effect of nanoparticles on dielectric properties of mineral oil is kept with accelerated thermal aging. For instance, Chen et al. [13] prepared oil-based nanofluids dispersing TiO_2 nanoparticles into a mineral oil. These nanofluids were aged at 130ºC for 6 days. The results of their work showed that the breakdown strength and partial discharge inception voltage (PDIV) of aged nanofluids can be increased up to 1.08 and 1.12 times compared with pure aged oil, respectively. Emara et al. [14] also carried out accelerated aging tests with mineral oil and TiO_2 nanoparticles. In their work, these authors exposed fresh mineral oil to accelerated aging tests at 120°C for two different aging periods, 3 days and 10 days. Then, aged oil-based nanofluids were prepared using TiO_2 nanoparticles. The main conclusions of this work were that a remarkable increase in breakdown voltage has been obtained as well as an important decrease of the dielectric dissipation factor. The addition of nanoparticles such as TiO_2 or ZrO_2 to mineral oil, also can modify thermal properties as discovered Pugazhendhi [15]. This author found that the breakdown strength, partial discharge inception voltage (PDIV), specific resistivity and kinematic viscosity of nanofluids suffered an increment in comparison with pure oil. However, the dielectric dissipation factor and the flash point were lower than mineral oil.

Although there are different works that have studied the dielectric performance of mineral oil based-nanofluids with TiO_2 nanoparticles, currently few works have prepared nanofluids using vegetable oils and TiO_2 nanoparticles [16]. One example is the work carried out by Nor et al. [17]. These authors presented the effect of TiO_2 particles on the breakdown voltages of Palm Oil and Coconut Oil. The results showed that these semiconductive nanoparticles improve the breakdown voltages of both vegetal oils. However, Nor et al. did not evaluated the effect of TiO_2 nanoparticles during thermal aging of nanofluids.

This novel work examines the performance of aged vegetable oil based-nanofluid which has been subjected to accelerated aging condition of 150ºC for 300 hours. Breakdown voltage, DC resistivity, permittivity, dissipation factor and acidity of nanofluid samples have been measured according to standard methods. Moreover, it has been analyzed the degradation of kraft paper through the degree of polymerization (DP) during the aging process. The comparison of dielectric performance between vegetable oil and nanofluid was done before and during the aging.

II. EXPERIMENTAL SETUP

The base oil used was a commercially available vegetal oil with the specifications described in Table I. The used TiO_2 nanoparticles were also commercially available, their characteristics are gathered in Table II.

TABLE I. SPEFICIFATIONS OF VEGETAL OIL USED FOR THE NANOFLUIDS

Property	***Specification***
Breakdown Voltage Kv	> 75
Kinematic Viscosity at 40ºC	37
Density at 20ºC	0.92
Pour point ºC	-31

TABLE II. SPEFICIFATIONS OF TiO_2 NANOPARTICLES

Property	***Specification***
Density (g/cm^3)	3,89
Morphology	spherical
Specific surface area (m^2/g)	> 120
Purity (%)	99.5
Average diameter (nm)	20

Oil-based nanofluid was prepared by mixing TiO_2 nanoparticles and vegetal oil. The dispersion was made uniform through an ultrasonic mixer for 7 hours. The nanoparticle content was 0.4 g/l.

Once the nanofluid had been produced, an accelerated aging test was carried out in an oven at 150ºC for 300 hours to examine ageing effects on the insulating performance of nanofluid and on the degradation of Kraft paper. The reference operating temperature of transformer oil in the field is considered as 60°C [18], therefore an increase above this temperature will raise the aging rate as it happens with pure dielectric oils [19, 20].

Once the nanofluid had been prepared it was added to steel containers where there were strips of Kraft paper (0.2 mmm thickness) previously dried in an oven at 100ºC for 24 hours. By means of a vacuum pump the air was extracted from the inside of the containers. Then the containers were filled with nitrogen. Finally, the steel containers were introduced into an oven at 150ºC. The thermal aging test of the nanofluid was compared with the carrier vegetal oil subjected to the same conditions as the nanofluid. The comparisons of dielectric properties, acidity and DP, between vegetal oil and nanofluid was done before and during aging.

III. RESULTS

Table III shows the initial properties of the vegetal oil (ester) and the nanofluid studied in this work.

Five samples of the vegetal oil and the nanofluid were taken to evaluate the progress of their aging at 150°C. Different parameters of the dielectric fluids were studied: dissipation factor, DC resistivity breakdown voltage, moisture and acidity. As for the paper condition, the analysis of its degradation was carried out through the measurement of the degree of polymerization (DP).

TABLE III. CHARACTERISTICS OF FLUIDS WITHOUT AGING

Fluid	**Characteristics**					
	Tan δ	***E***	***DC Resistivity***		***Moisture***	***Acidity***
	-	-	*GΩ-m (+)*	*GΩ-m (-)*	*ppm*	*mg KOH/g*
Ester	0.030	2.80	4.91	4.725	495.10	<0.07
Ester +TiO_2	0.080	2.80	5.60	5.20	438.2	0.2

A. *Dissipation Factor (IEC 60247)*

Dielectric dissipation factor is a suitable tool to indicate the quality of insulation. A high value of this parameter is an indication of the presence of contaminations or deterioration products such as water or oxidation products. Fig. 1 shows the evolution of the dissipation factor during the thermal aging of the vegetal oil and the nanofluid. It can be observed that the nanoparticles increase the dielectric dissipation factor of the vegetal oil.

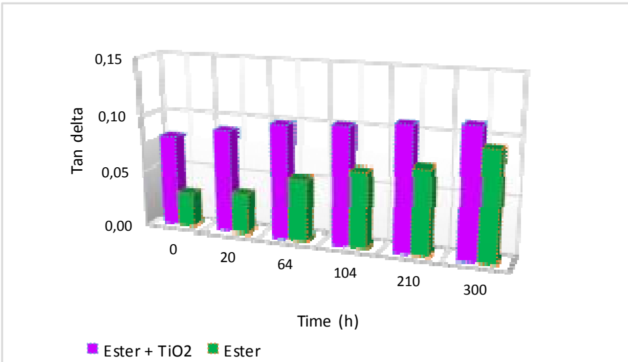

Fig. 1. Evolution of dissipation factor over time at 150°C

This result verifies the adverse effect of nanoparticles on the dissipation factor of the studied vegetal oil. The dissipation factor of the nanofluid is worse than that of the pure ester during the whole aging period. The difference in the response of both liquids is reduced as the aging progresses. This could be due to nanoparticles deposition/agglomeration which was visually observed on the bottom of the vessel containing the nanofluid.

B. *DC Resistivity (IEC 60247)*

The resistivity of an insulation material is the ratio between the intensity of a continuous electric field and the steady state value of the current density in the material and it is the most sensitive property of oil requiring utmost care for its proper determination. A low value indicates the presence of moisture and conductive contaminants.

This parameter has been measured over time for both dielectric fluids and in both polarities, obtaining quite similar results (Fig. 2 and 3). The nanofluid always presents lower resistivity than that of vegetal oil during aging. Analyzing the trends, it is observed that as the nanofluid degrades, its resistivity is closer to the vegetal oil one. This could be due to nanoparticles deposition/agglomeration.

C. Breakdown Voltage (IEC 60156)

The breakdown voltage test is generally used as acceptance test before filling the oil inside the transformers. This test was performed using stainless steel electrodes which were set 2.5 mm apart. The breakdown test values depend on the moisture content and other impurities present in the sample. This parameter serves to decide on the possibility of carrying out a drying and filtration treatment. In the laboratory experiments, it has been observed, Fig. 4, that the addition of nanoparticles in dielectric vegetal oil generally improves the dielectric strength, especially after 150 hours of aging.

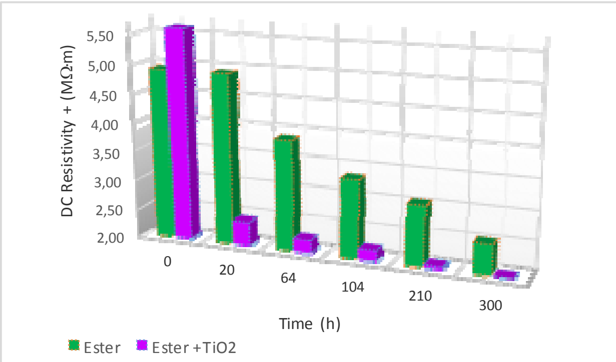

Fig. 2. Evolution of DC Resistivity (+) over time at 150°C

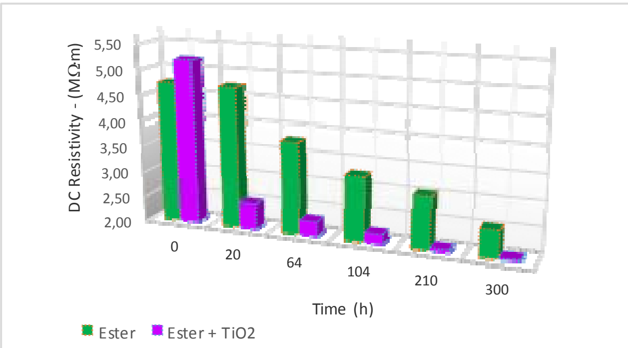

Fig. 3. Evolution of DC Resistivity (-) over time at 150°C

D. Moisture (IEC 60814)

Analyzing the results of Fig. 5, it can be observed that the moisture content in the nanofluid is slightly higher than that of the vegetable oil for most of the aging period. Analyzing the behavior of these samples, it is verified an important increase of the moisture in the early stages of the process. This is caused because water is a byproduct of oil and paper degradation, which seems to be enhanced by the presence of particles. Subsequently this content decreases gradually, reaching similar values in both fluids, less than 200 ppm at the end of aging.

The significant reduction of moisture in the dielectric fluids from 64 to 100 hours of aging helps to explain the increase in dielectric strength despite having more degraded liquids.

E. Acidity (IEC 62021)

Acidity is a property whose value is a consequence of the byproducts of dielectrics degradation. In turn, this property is also one of the causes that favor the degradation of insulation systems and this is the reason why its value is limited in those fluids of dielectric application.

As with dissipation factor, the nanofluid has a higher acidity than vegetal oil, Fig. 6, which produces a greater degradation of the oil. Therefore, the presence of nanoparticles catalyzes the degradation of dielectrics.

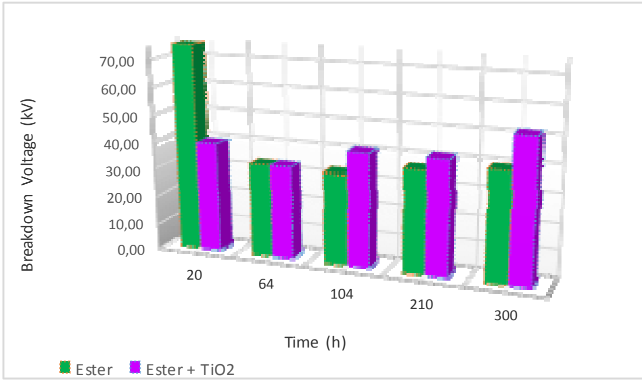

Fig. 4. Evolution of Breakdown Voltage over time at 150°C

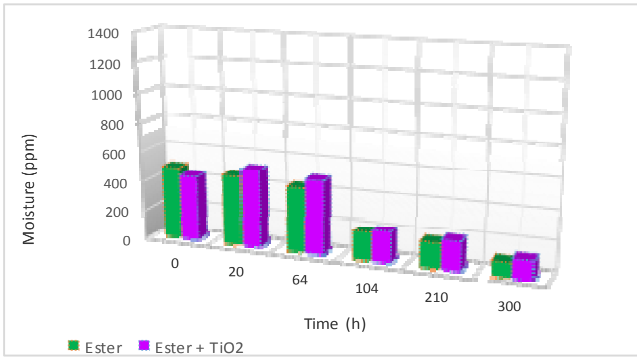

Fig. 5. Evolution of Moisture over time at 150°C

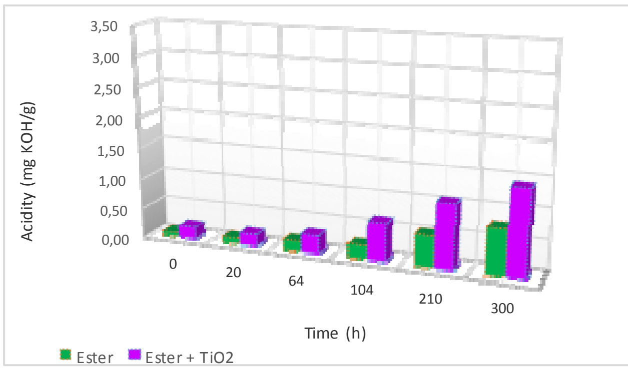

Fig. 6. Evolution of Acidity over time at 150°C

F. *Degree of Polymerization (IEC 60450)*

The degree of polymerization (DP) can be defined as the number of average monomers present in a cellulose molecule. This property is an indirect measure of the mechanical strength of the paper and therefore of its state of degradation.

Fig. 7 shows the evolution of the DP throughout the aging period. These results corroborate, that the values of DP of the Kraft paper aged with the pure vegetal oil are 1.18 times as those of Kraft paper aged in the TiO_2 nanofluid. Therefore, the nanoparticles raise the degradation rate of Kraft paper. A possible explanation for this higher degradation, which causes more acidity, higher dissipation factor and lower resistivity, may be that the nanoparticles act as hot spots, promoting the thermal degradation of the dielectrics.

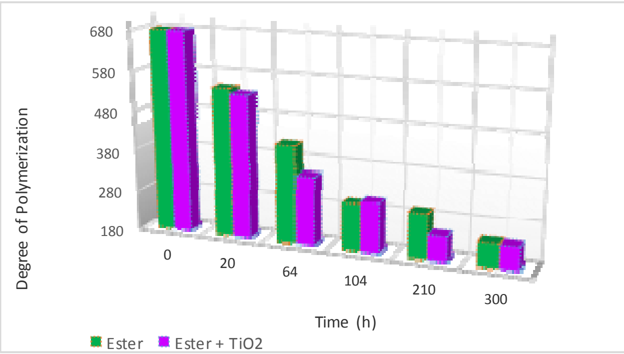

Fig. 7. Evolution of Degree of Polymerization over time at 150°C

IV. CONCLUSIONS

It could be concluded that nanoparticles increase the values of ageing indicators such as dissipation factor and acidity, as well as reduce the degree of polymerization of dielectric paper, which indicates higher degradation of paper. However, the use of nanoparticles increase the value of breakdown strength that is essential for a suitable performance of power transformers.

A critical issue visually observed during aging period was particle deposition/agglomeration on the bottom of the vessels containing nanofluid, a hint that the nanofluid prepared was unstable over aging time.

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