Dielectric Properties of PVC/Al_2O_3 Nanocomposite Under the Influence of Thermal Aging

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Abstract- Under service conditions impact, insulated power cables can undergo critical degradations. It is now well-established that temperature is one of the key degrading factors which affect the properties of electrical insulation materials. In this study, the thermal aging of polyvinyl chloride (PVC)/Aluminum Oxide (Al_2O_3) nanocomposite has been investigated. For this purpose, the PVC samples with Al_2O_3 additive, prepared with different concentrations (0, 2.5, 5 and 7.5 wt. %), subjected to elevated temperatures have been investigated. Indeed, the dielectric behavior was quantified by measuring and evaluating the dielectric permittivity (ε'), dielectric loss factor (tanδ) and dielectric loss index (ε") as function of aging time and frequency. Obtained results demonstrated that adding Al_2O_3 improves the dielectric properties of PVC and limits its degradation under thermal aging.

I. Introduction

Recently, researchers have been motivated to improve the mechanical, electrical and physical properties of polymers due to the growing demand in the industry and applications [1]. In the last few decades, the utilization of polymeric materials as power cables insulation saw significant growth [2]. Among these polymers, PVC is one of the most extensively used as an electrical insulating material for low and medium voltage cables [3]. The widespread use of PVC is due to its excellent properties such as its ability in flame retardancy [4] and its superior mechanical performance [5]. Despite its excellent properties, PVC presents some limitations such as brittleness, poor processability and poor thermal stability which can affect its applications in electrical power equipment. Under service conditions, PVC-insulated cables are exposed to thermal aging. This stress leads to gradual degradation of the insulation, which rapidly reduces its lifetime [6]. To overcome this shortfall, the PVC overall properties can be improved by introducing the nanofillers to the PVC matrix to form PVC nanocomposites or PVC nanodielectrics [7], [8]. However, despite the role that nanofillers play in improving the performance of PVC, the properties of nanocomposites can be affected during thermal aging. Therefore, long-term testing of PVC nanocomposite materials is essential prior to their practical application.

In this work, the effect of long-term thermal aging on the dielectric properties of PVC/Al_2O_3 nanocomposite is studied. The article is organized as follows: Experimental section presents the experimental setup. In the Results and Discussion section, the collected experimental results are illustrated and discussed. The Conclusion section summarizes the key findings.

II. Experimental

The PVC/Al_2O_3 nanocomposites were prepared by introducing different filler amounts, respectively, 2.5 and 5.0 wt% into a PVC matrix. The choice of 2.5 and 5.0 wt% concentrations of Al_2O_3 filler in PVC matrix for the preparation of nanocomposites is typically based on avoiding issues such as aggregation of nanoparticle. The PVC/Al_2O_3 is obtained using a calendring machine, type Polymix 200 P. The machine is equipped with two visible rollers that allow polymer lamination. Their temperature can be adjusted independently using the controllers, and in our case, the temperature is set at 170°C. The heated rollers ensure the polymer material melts. In our case, the preparation of the material is carried out at a processing temperature of 165°C by mixing the PVC and Al_2O_3 pellets with the desired dosage and introducing them together onto the heated rollers for about 15 minutes. The final material has a thickness of approximately 1.5 mm.

Fig. 1: The calendring machine used for the preparation of the PVC nanocomposites

Thermal aging experiments were conducted using a thermo-ventilated oven that was fixed at a constant temperature of 95 ± 2 °C. The samples were placed vertically and heated in the oven for 2400 hours.

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Fig. 2: View of the experimental setup used for the thermal aging

The studied material was characterized by using an LCR meter (Instek-LCR 817 type). The LCR meter was set up to measure the samples' capacitance and dielectric loss factor (*tanδ*) between 10^1 and 10^4 Hz. The following formulae were used to determine the dielectric constant (ε') and dielectric loss index (ε''):

$$\varepsilon' = \frac{d}{A.\varepsilon_0}.C \qquad (1)$$

$$\varepsilon'' = tan\delta.\varepsilon' \qquad (2)$$

where d, A, C and ε_0 are the sample thickness, area of sample, the capacitance of sample and the permittivity of free space (8.85×10^{-12} F/m), respectively.

III. RESULTS AND DISCUSSION

Figure 1 shows the variation of the dielectric properties of the unaged sample, specifically the dielectric permittivity, dielectric loss factor and dielectric loss index, as a function of frequency. The presented results correspond to different concentrations of Al_2O_3 (0%, 2.5% and 5%).

As can be observed in Figure 1.a, the addition of Al_2O_3 to the PVC matrix can either increase or decrease its dielectric permittivity. This effect depends on the permittivity of the added filler. This phenomenon was reported by Mansour *et al.* [9] when studying the dielectric properties of PVC/ZnO nanocomposites. The dielectric permittivity of PVC nanocomposites is generally influenced by both the permittivity of the filler material and the degree of nanoparticle agglomeration [10]. The decrease in dielectric permittivity with increasing frequency can be attributed to the difficulty of dipolar groups—particularly the larger ones—in reorienting in the same direction of the applied field which reduces their contribution to the overall permittivity at higher frequencies [11].

From Figure 1.b, it can be observed that the addition of Al_2O_3 nanoparticles to PVC increases the dielectric loss factor. This may be attributed to interfacial polarization effects at the polymer–nanoparticle boundaries, which enhance charge trapping and contribute to higher dielectric losses [12]. The dielectric loss factor of PVC nanocomposites remains practically constant with frequency. This can be assigned to the induced structural changes which can restrict the mobility of dipolar groups. As a result, these dipoles are less responsive to changes in frequency, leading to a relatively stable dielectric loss factor across the frequency range.

The dielectric loss index shown in Figure 1.c provides information on the power lost in the material. Therefore, any change in this index as a function of nanofillers amount corresponds to a variation in the power loss. In fact, dielectric loss results from the molecules in the polymer matrix, known as dipoles, not being able to fully track changes in the applied electric field. The dipoles do not immediately realign themselves when the field changes, which causes energy to dissipate as heat. The material's power loss is directly reflected in this energy dissipation. It can also be seen that, as with the dielectric loss factor, the loss index decreases with increasing frequency. This behavior can be due to the dipolar relaxation mechanism [13].

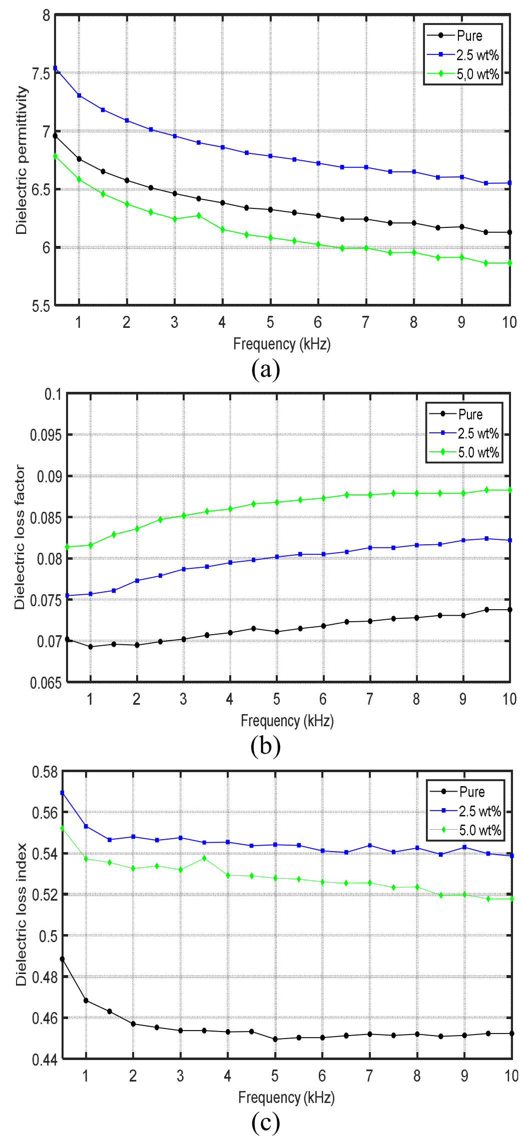

Fig. 1: Evolution of the dielectric properties of unaged pure and reinforced PVC

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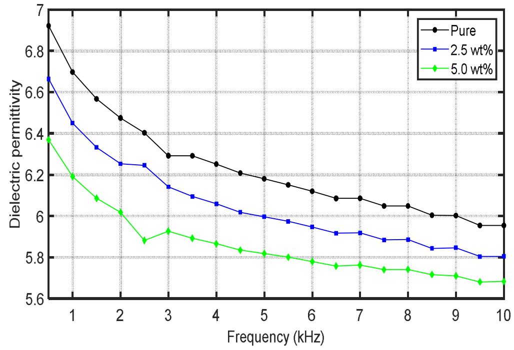
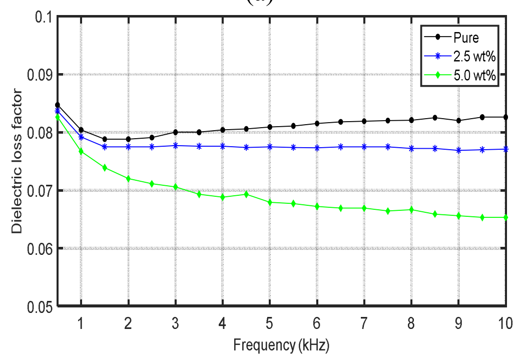
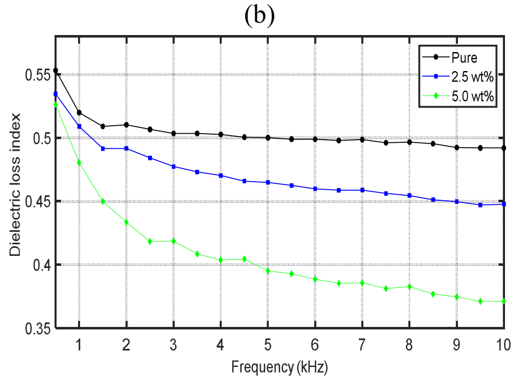


(a)



(b)



(c)

Fig. 2: Evolution of the dielectric properties of pure and reinforced PVC after 2400 hours of thermal aging

Figure 2 depicts the frequency-dependent behavior of the dielectric properties, namely, dielectric permittivity, dielectric loss factor and dielectric loss index of samples thermally aged for 2400 hours. The results are shown for varying Al_2O_3 concentrations of 0%, 2.5%, and 5%.

As can be seen in Figure 2.a, the dielectric permittivity decreases with aging times for all the Al_2O_3 amounts compared to the unaged samples. This decrease can be attributed to the structural rearrangement [14]. The decrease of dielectric permittivity as a function of frequency is due to the shortening of the time needed for the dipoles to orient themselves in the direction of the applied electric field [1].

Figure 2.b shows that the dielectric loss factor increases with thermal aging for all the Al_2O_3 concentrations. This characteristic for pure PVC is higher than that of PVC/ Al_2O_3 nanocomposites. So, it can be concluded that the degradation of PVC/Al_2O_3 nanocomposite samples will occur after a longer period of thermal effect as compared with the pure PVC sample. As can be seen from Figure 2.c, the dielectric loss index exactly follows the variation trend of the dielectric loss factor. Indeed, an increase or decrease in the loss factor corresponds to an increase or decrease in the loss index. These variations correspond to the energy lost by the Joule effect in the PVC. On the other hand, the dielectric loss index progressively decreases with increasing frequency. The decrease is more pronounced at low frequencies. This decline is thought to be due to the dipole relaxation phenomenon occurring in material [15]. In fact, the field fluctuates so quickly at high frequencies that the dipoles are unable to keep up with the oscillating field. They will try to realign with the field, but they are unable to do so effectively because of friction and inertia (interactions with other dipoles, polymer chains, and the filler material). A lower dielectric loss index and less energy dissipation are the results of this misalignment between the dipole's orientation and the oscillation of the field.

IV. CONCLUSION

This study investigated the effect of thermal aging on PVC/Al_2O_3 nanocomposites. The analytical evaluations were carried out by measuring dielectric permittivity, dielectric loss factor and dielectric loss index. Based on the experimental results obtained from the characterization techniques, the key findings can be summarized as follows:

For the unaged sample, the dielectric permittivity decreased by adding 5wt% of Al_2O_3. The dielectric loss factor and dielectric loss index increased by adding 2.5 and 5wt% Al_2O_3.

After 2400 hours of thermal aging, all the dielectric properties have been improved. The results showed a decrease in both dielectric permittivity, dielectric loss factor and dielectric loss index. All the properties are higher for pure PVC. This result confirms that the degradation of PVC/Al_2O_3 nanocomposite samples will occur after a longer period of thermal effect as compared with the pure PVC sample.

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