Numerical and experimental evaluation of dielectric properties of thermally aged insulating paper used in power transformers

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***Abstract*- Due to the relevant role of the cellulosic insulation in the dielectric system of a power transformer, it is necessary to know its dielectric properties and its evolution as insulating material. The dependence of the dielectric properties of solid insulation on the moisture content, temperature, or pressure is well-defined. However, it is not clear the effect of the paper degradation on its insulating capacity. To study the impact of ageing on the dielectric properties, samples of Kraft paper were subjected to an accelerated hygrothermal ageing. Degree of polymerization (DP) value was reduced from 1000 to 200, with intermediate study points. All samples were conditioned to the same moisture content in order to only evaluate the effect of the paper degradation. Different dielectric properties, such as loss factor (tan δ) and complex permittivity (ε) were measured using the dielectric spectroscopy technique. These experimental results were used to develop a numerical model with the finite element-based tool Comsol Multiphysics. This model provided some extra information about the material properties, such as the electric field distribution. Results showed that the degradation of Kraft paper modifies its dielectric response.**

I. Introduction

Power Transformers are extremely expensive machines, so users and manufacturers have invested resources in understanding and defining their components behaviour. One of their critical elements is the dielectric system, composed basically of cellulosic materials impregnated with oil. Cellulosic materials cannot be replaced without disassembling the windings, with the consequent operational and economic damage, so the end of machine's life is defined by the solid insulation. The optimal operation of the transformer is highly dependent on its insulating system. In fact, the dielectric failures are the most common faults in these machines, [1].

Dielectric properties of solid insulation are affected by temperature, time, pressure, or moisture. It is well known that increases of these parameters induce an increase in the paper loss factor. In fact, the influence of moisture on the dielectric response of solid insulation has been widely studied, e.g. [2], [3].

During transformer operation, cellulosic materials are subjected to different stresses, such as high temperatures, moisture or electric fields that lead to their degradation. Even though this ageing cannot be avoided, its effect on the dielectric behaviour of the solid insulation is not clear. Some authors have tried to establish this relationship, [4]–[6]. Since these latter studies found different results when quantifying the effect of DP on the dielectric properties, it is not possible to drawn clear conclusions.

Dielectric spectroscopy is combined with degree of polymerization (DP) technique in several of these papers to carry out the studies. Based on the previous works, this paper analyses the dielectric properties of several samples of Kraft paper with different ageing levels. Contrary to previous studies, where the relationship between ageing and dielectric response was studied under non-controlled conditions of cellulose moisture content, [7], samples with the same moisture content are compared. The objective is to discriminate the effect of the degradation from the one of moisture.

In addition to the experimental data, complementary dielectric information can be obtained using numerical techniques. There are not many papers that use these techniques for this purpose, e.g. [8]. This paper presented two numerical models –micro and macro-scale- which allowed the determination of frequency-dependent dielectric properties of a composite material with stochastic structure in the frequency range from 1 mHz to 1 kHz. Since insulation paper can be considered such a material, a numerical model based on Finite Element Method (FEM) was developed using the software tool COMSOL Multiphysics. This model replicates the experimental frequency domain analysis and allows to obtain complementary dielectric results to those get by spectroscopy.

II. Experimental Setup

A. *Samples preparation*

The experimental procedure is shown in Figure 1. First, Kraft paper was cut in 7 cm x 7 cm samples. Then, samples were subjected to an accelerated thermal ageing in a fan oven at 150 ºC with different ageing times: 0, 12, 24, 48, 72, 144, 216 and 312 hours.

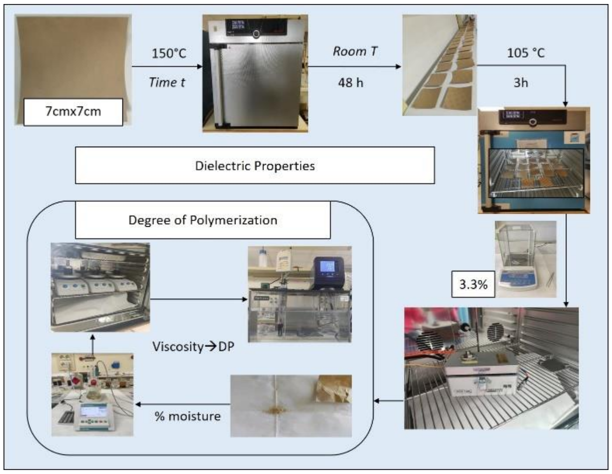

Fig. 1. Experimental procedure.

B. Characterisation

Once the ageing process finished, samples were kept at ambient conditions during at least 48 h. Then, they were dried in a fan oven during 3 h. at 105 ºC. After that, they were again kept under ambient conditions until they reached the desired moisture content -fixed at 3.3%-, calculated using eq. (1).

$$W_{H_2O}(\%) = \frac{m_m - m_d}{m_m} * 100 \qquad (1)$$

where m_m and m_d are the mass of the wet and dried sample, respectively, and W_{H_2O} is its moisture content.

This way, the dielectric analysis of all the samples was carried out at the same ambient humidity and temperature -25ºC- conditions, thus discriminating the ageing effect from that of the moisture on the dielectric response.

The frequency analysis of the samples was carried out by a dielectric spectroscopy analyser (Spectano 100) connected to a sample holder (DSH 100), both from the trademark Omicron. Thirty-two frequencies in the range from 0.01 Hz to 5 kHz were analysed, and the peak voltage applied between the electrodes was 50 V.

Finally, the paper degradation was measured by means of the determination of its DP according to the ASTM D4243 standard, [9]. Results of DP tests are shown in Figure 2. As it can be seen in this Figure, the paper was degraded until the end of its useful life, expressed as a percentage of the initial degradation, DP_0 (1000).

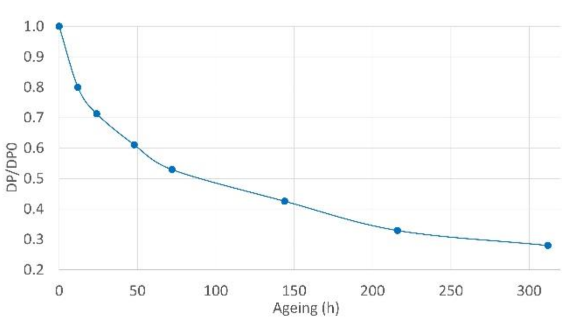

Fig. 2. DP of Kraft paper samples after different ageing times.

C. Experimental dielectric results

Results of the dielectric loss factor (tan δ) and the imaginary part of complex permittivity, ε”, were obtained by dielectric analysis. The percentage change of tan δ is represented in Figure 3, comparing the aged samples with the new one. Results showed that the dielectric losses of Kraft paper increased with the ageing, up to 50% at industrial frequency. If percentage change of ε”, which represents the dielectric losses, is considered, Figure 4, the losses increased in almost 75%.

III. EXPERIMENTAL SETUP

This section presents the description of the numerical model that allows to visualize the electric field distribution inside the samples and to determine also complementary numerical results, e.g., absolute dielectric losses or relative permittivity, typically used as comparative properties between materials.

A. Computational domain and mesh

As can be seen in Figure 5, a 2D axisymmetric section of the dielectric sample holder was used in the electric model. Paper, air, and electrodes with guard ring were modelled.

A fine mesh of 622527 triangular elements was defined with an average element quality of 0.9643.

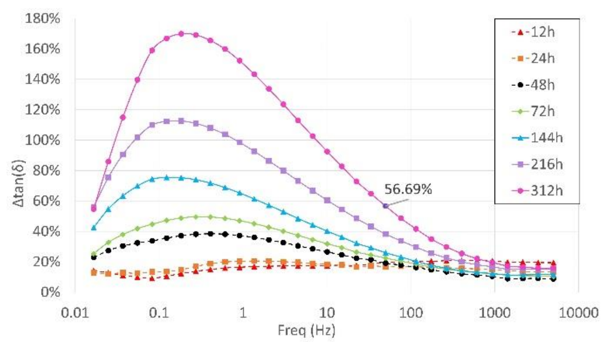

Fig. 3. Percentage change of Loss Factor

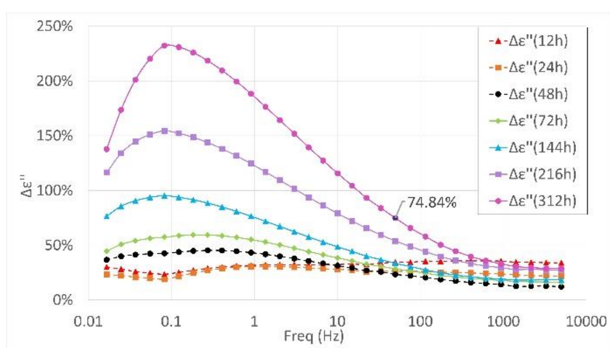

Fig. 4. Percentage change of imaginary part of complex permittivity

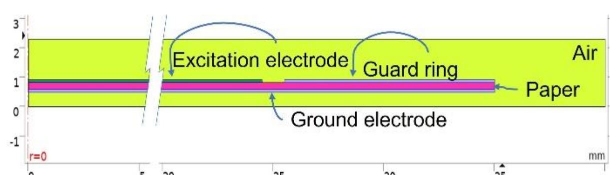

Fig. 5. Geometry of the model: air, excitation electrode, ground electrode, guard ring and paper.

B. Equations

The FEM solved a current conservation problem posed by the eq. of continuity for the electrical potential, eq. (2), considering both conduction and displacements current densities, eq. (3).

$$\nabla \cdot \boldsymbol{J} = Q_{j,v} \tag{2}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E} + j\omega \boldsymbol{D} + \boldsymbol{J_e} \tag{3}$$

$$\boldsymbol{E} = -\nabla V \tag{4}$$

Where $\boldsymbol{J}$, $Q_{j,v}$, σ, $\boldsymbol{E}$, ω, $\boldsymbol{D}$, $\boldsymbol{J}_e$ and V are current density, volumetric loss density, conductivity, electric field, angular frequency, electric displacement field, external current density and electric potential, respectively.

The approximate solution of the partial differential equation was obtained using the commercial solver *Comsol Multiphysics 5.5*. Frequency Domain study was executed. Experimental frequencies were used to validate the numerical model by comparison.

C. Materials

Although paper is a heterogeneous material composed basically by cellulose fiber, water, and air, it was considered in the model as a homogeneous dielectric. That is, as can be seen in Table 1, bulk electric properties were taken into account to model this material. The real and imaginary parts of the complex permittivity of the samples were experimentally obtained from the frequency analysis. Regarding the electrical conductivity of the samples and air, values from the Comsol Multiphysics database were used. In addition, the relative permittivity of the air was taken from this database.

D. Boundary conditions

Regarding boundary conditions, axial symmetry (no-flux) and electric insulation (no electric current) conditions were applied on all the boundaries of the symmetry axis and on external model boundaries, respectively. Also, zero potential was applied on the contours of the ground electrode and the guard ring. Finally, a sinusoidal source of 50 V_{peak} was applied on the excitation electrode.

TABLE I
DIELECTRIC PROPERTIES OF THE MODEL MATERIALS

Property / Material	Electrical conductivity μ, Ps/m	Complex permittivity	
		Real Part ε_r	Imag. part ε_i
Kraft paper	2	Exper. data	Exper. data
		Relative permittivity	
air	0	1	

E. Model validation

The validation of the electromagnetic model was carried out by comparison of the experimental results of resistance and capacitive reactance with those calculated numerically for all the frequencies and ageing levels. Numerical error remained below 3.06% (R) and 1.98% (X_c) in the worst case, which corresponds to the sample aged for 144h at 0.01662 Hz. As can be seen in these figures, the error is pretty small, allowing the validation of the model.

F. Numerical results

As mentioned in the introduction, complementary results can be obtained from the numerical model, e.g., the absolute dielectric losses that are shown in Figure 6. According to this Figure, as the frequency increases, so do losses. If percentage change of losses is represented, the increase of losses with ageing can be appreciated, as shown in Figure 7. These results show that the percentage change of imaginary part of complex permittivity (Figure 4) is the same as percentage change of absolute losses.

As can be seen in Figure 8, it is also possible to obtain the relative permittivity using eq. (5). This parameter seems to evolve positively with ageing: the greater the ageing, the higher is the permittivity. Relative permittivity given by COMSOL agrees with the same parameter obtained with the experimental results using eq. (5).

$$\varepsilon_r = \frac{C}{C_0} = \frac{{}^{1}/_{(2 * \pi * f * X_c)}}{\varepsilon_0 * {}^{A}/_{h}} \tag{5}$$

Where C, C_0, f, X_c, ε_0, A y h are capacity of sample, capacity of vacuum, frequency, capacitive reactance, vacuum permittivity, and area and height of the sample, respectively.

Also, as can be seen in Figure 9, the numerical model can provide graphical information, such as the electric field distribution in the paper sample. According to this Figure, this parameter is almost constant between electrodes, varying at the edge of the small electrode. Other variables such as current density or electric displacement field have similar distributions to that shown in Figure 9.

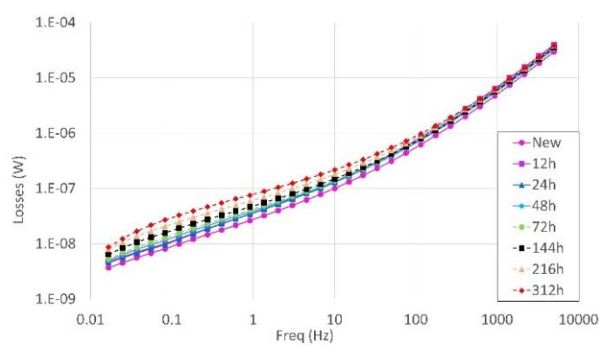

Fig. 6. Absolute dielectric losses.

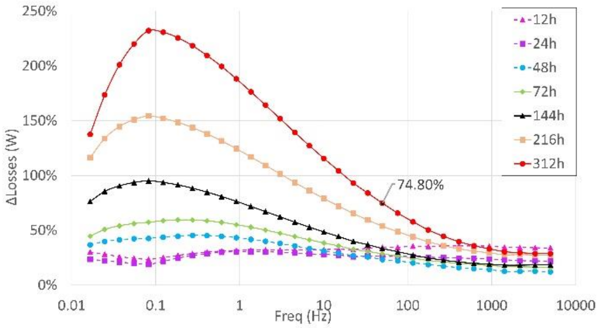

Fig. 7. Percentage change of absolute losses.

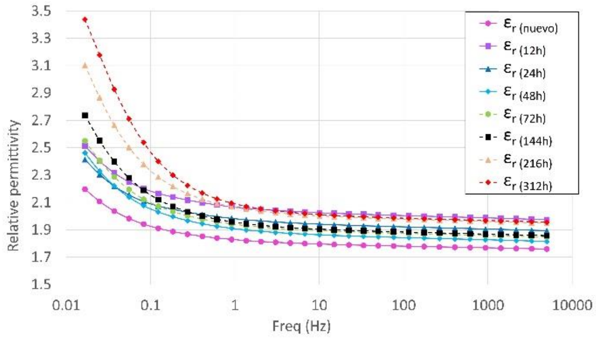

Fig. 8. Evolution of the relative permittivity with aging.

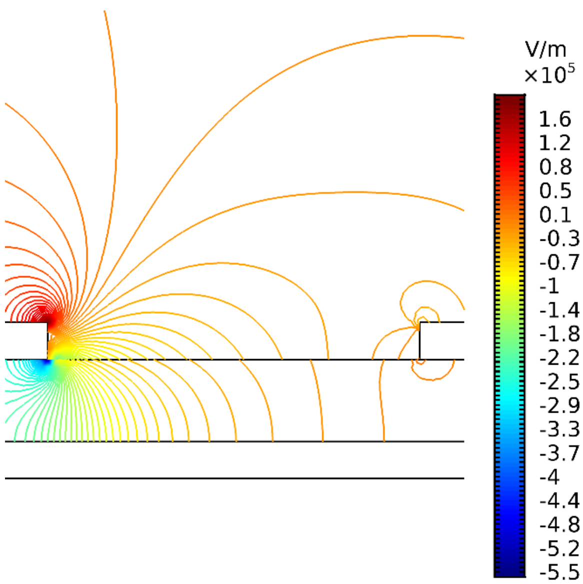

Fig. 9. Electric field (V/m) in Kraft paper at freq=5000Hz.

IV. Conclusions

Dielectric properties of new and aged Kraft paper were analysed in this paper. All samples were conditioned to the same internal moisture content to analyse only the effect of ageing.

Results showed that the ageing affects the dielectric properties of insulating paper, increasing not only its dielectric losses but also its relative permittivity.

Also, a numerical model was developed and validated with the experimental data. It has been demonstrated that numerical methods can be useful to get complementary information to that obtain experimentally about the dielectric properties of insulating materials.

Future work will be carried out including new materials, as different solid insulation composed with cotton or resin. Also, the effect the impregnation has on the dielectric response will be considered, both in new and aged conditions.

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