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Research Article

Loss Factor Behavior of Oil Impregnated Paper Under the Effect of Temperature and Aging using Frequency Domain Spectroscopy

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Abstract – Power transformer is crucial and expensive electrical transmission component. Regular maintenance is essential for prolonging the operational lifespan of this device. Dielectric testing techniques are a tool for evaluating and predicting the condition of transformer insulation systems. This paper investigates loss factor variation for two types of oil-impregnated paper used in power transformers, kraft and pressboard. During laboratory experiments, dielectric loss values were examined at different temperatures and thermal aging based on frequency domain spectroscopy (FDS) with a frequency range from 0,01Hz to 1000Hz. The results showed that temperature and aging are two significant factors that influence the loss factor and the quality of the insulation of paper. In addition, these experiments revealed that a correlation exists between frequency and these two factors. Such correlation can be utilized for better prediction of paper insulation lifetime.

Keywords – Power Transformer, Oil-Paper İnsulation, Aging, Temperature, Loss Factor, Frequency Domain Spectroscopy.

I. INTRODUCTION

Power transformers are a highly costly component inside power systems, serving a crucial function in facilitating the uninterrupted transmission of electricity [1]. The dependable functioning of a power system is contingent upon the health of the transformer. The health of a transformer is reliant upon its insulation system, which plays an essential part in enhancing the transformer's operational efficiency. Therefore, The effective utilization of insulating materials within a transformer is essential for achieving optimal performance. Several elements can contribute to the sudden failure of a transformer, including temperature, humidity, acidity, contamination of oil, oil viscosity, oil breakdown voltage, and the degree of polymerization in the cellulose paper. [2].

The lifespan of a transformer is closely linked to the quality of its insulation. Consequently, the application of condition monitoring techniques to assess the state of the insulation and estimate the remaining lifetime of a transformer is an appropriate strategy. In the present context, the sufficiency of current diagnostic tools and the implementation of novel monitoring strategies are progressively gaining significance.

The insulation materials used in power transformers predominantly comprise solid insulation, which is formed of various cellulose-based materials such as Kraft paper and pressboard. Additionally, the liquid insulation typically employed is mineral oil [3]. Oil serves as an insulating medium, effectively dissipating heat generated by the transformer core, while also protecting the cellulose paper. Cellulose paper functions as a dielectric material in transformers, wherein it retains electrical charge during energization. Also, it enhances the thermal health of the transformer by the creation of cooling ducts for the oil[4]. Paper is mostly made of cellulose, the cellulose is an organic substance composed of glucose molecules that are interconnected to create a linear polymeric chain. The polymeric chains are denoted by the chemical formula $[C_6H_{10}O_5]_n$, where the variable n represents the average quantity of glucose rings present in the molecule and is quantified in terms of the degree of polymerization. The service life of the transformer is primarily influenced by the condition of the oil-paper insulation, which can be impacted by several aging mechanisms including electrical, thermal, chemical, mechanical, and environmental factors. [5].

Thermal aging is widely recognized as the primary mechanism accountable for the deterioration of transformer insulation over time. The primary cause of thermal degradation of cellulose in oil-filled electrical equipment is the occurrence of chemical reactions resulting from oxidation and hydrolysis. The presence of oxygen, water, and acids in contact with cellulose significantly affects the rate of these reactions. During the process of heat degradation, the formation of aldehydes and carboxyl groups is observed, accompanied by the release of carbon dioxide. Upon subjecting cellulose to elevated temperatures, the thermal energy induces the cleavage of glycosidic linkages, resulting in the formation of degradation byproducts including carbon dioxide, carbon monoxide, water, hydrogen, and small quantities of methane. The remaining groups of cellulose chain can undergo interaction with oil components, resulting in the formation of various compounds such as sludge, acids, polar groups, and so on [6]. Both of these factors have the potential to influence the dielectric characteristics of the insulation material.

II. Frequency Domain Spectroscopy and Loss Factor

Dielectric dissipation factor called loss factor, generally expressed as a loss tangent and tan delta, is one of the most significant tools for assessing the state of solid/liquid insulation. Losses in an insulation material refers to the energy that is converted into heat in the medium, and manifest when it is exposed to an alternating voltage (AC). The occurrence of these can be attributed to the presence of a loss component I_R, of the dielectric current. This element is characterized by an angle δ, which represents its deviation from the purely capacitive current I_C. Mathematically, the relation between I_R and I_C can be expressed as $I_R = I_C * \tan(\delta)$ [7]. Fig. 1 illustrates the phasor diagram and equivalent circuit of a dielectric.

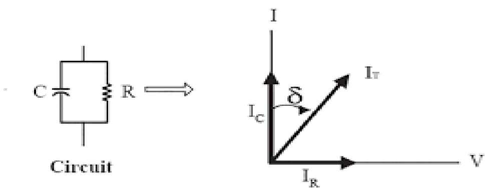


Fig. 1 Phasor diagram and equivalent circuit of a dielectric

The tangent of the angle serves as a measurement for quantifying dielectric losses W:

$$W = U \cdot I_C \tan\delta = U^2 \omega C \tan\delta \qquad (1)$$

Where: C is the capacitance of the insulator, U– phase voltage. Capacitance can be expressed as:

$$C = \frac{\varepsilon . A}{d} \qquad (2)$$

Where: A is the plate area of the capacitance, ε is the complex permittivity and d is the distance between the two plates. The losses are proportional to the loss tangent tanδ

$$\tan\delta = \frac{I_r}{I_c} = \frac{1}{\omega . R . C} \qquad (3)$$

Measurements of loss factors at a single frequency provide only a restricted evaluation of the insulation condition, making it impossible to differentiate between distinct effects [8]. This is why the use of frequency-dependent spectroscopy is necessary. Frequency Domain Spectroscopy (FDS) is a technique employed to investigate the dielectric polarization and complex capacitance dielectric loss across various frequencies. The Frequency Domain Spectroscopy (FDS) approach offers several notable benefits, including robust anti-interference capabilities, a broad frequency range, low voltage requirements, and rich information content. Consequently, FDS has found extensive utilization in the online assessment of transformer insulation conditions [9].

This technique involves the measurement of the frequency-dependent complex capacitance C(ω) or permittivity ε(ω) while subjecting the system to a sinusoidal excitation with different frequencies. The relationship between the applied voltage U(ω) and the measured capacitance/permittivity can be mathematically expressed through equations (4) and (5) respectively [10].

$$I(\omega) = j\omega(\underbrace{C'(\omega)}_{\text{real}} - j\underbrace{C''(\omega)}_{\text{imaginary}})U(\omega) \tag{4}$$

$$I(\omega) = j\omega(\underbrace{\varepsilon_\infty + \chi'(\omega)}_{\text{real } \varepsilon'(\omega)} - j\underbrace{\left(\sigma/\varepsilon_0\omega + \chi''(\omega)\right)}_{\text{Imaginary } \varepsilon''(\omega)})C_0U(\omega) \tag{5}$$

In this context, ε_∞ and σ represent the high-frequency relative permittivity and the conductivity of the material being examined, respectively. Further, the ω= 2π*f* represents the angular frequency. The expression (χ(ω)=χ′(ω) -jχ″(ω)) denotes the frequency-dependent relative susceptibility. ε_0 represents the dielectric permittivity of free space. The value of C_0 is the geometrical capacitance of the test object, which is 20.136 nF.

The process of quantifying the dielectric loss factor entails the calculation of the ratio between the imaginary component of impedance and the real component of impedance. The complex capacitance and permittivity can be utilized to present it in the following manner:

$$\tan\delta(\omega) = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} = \frac{C''(\omega)}{C'(\omega)} = \frac{\frac{\sigma}{\omega\varepsilon_0} + \chi''}{1 + \chi'} \tag{6}$$

where σ_o is the dc conductivity of the dielectric material, ε_o = 8.852 10^{-12} is the vacuum permittivity, ε' (ω) and ε''(ω) are real and imaginary parts of the complex permittivity.

III. Sample Preparation and Experimental Setup

Fig. 2 illustrates the measuring setup of the IDA 200 using the FDS method. The main operation of the IDA 200 is to assess the impedance of insulation at a specified frequency and voltage level. These measured values are subsequently utilized for the computation of insulation capacitance and dissipation factor. The previous process is iterated throughout a range of frequencies. The circuit depicted above demonstrates the ability to measure voltage and current using a voltmeter and electrometer, respectively. Additionally, the impedance value may be calculated using Ohm's law.

$$Z = \frac{U}{I}$$

The diagnostic measurement is done by applying a relatively low voltage up to 140V, the frequency range of IDA 200 is from 0.0001 to 1000 Hz. The basic measurement principle of FDS is shown in Fig. 2.

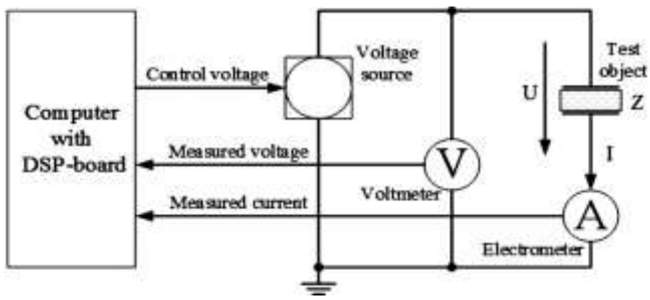


Fig. 2 FDS measurement circuit diagram of the oil paper insulation system of transformer

The generation of a test signal with the desired frequency is performed by a Digital Signal Processing (DSP) unit. The signal undergoes amplification by an internal amplifier before being applied to the specimen. The voltage across and the current flowing through the specimen are accurately measured using a voltage divider and an electrometer. By employing this approach, the method effectively mitigates the impact of noise and interference. Consequently, the IDA 200 system allows operation at voltage levels up to 140 V while maintaining accuracy and comprehensiveness in its analytical capabilities.

Laboratory-based accelerated aging techniques can effectively diminish the longevity of both liquid and solid insulation systems. The utilization of an accelerated vessel aging technique has several advantages, including a faster rate of aging, reduced costs, and the ability to get samples with a precisely controlled thermal history.

Masse du papier = 10 % de la masse d'huile = 10 % densité d'huile *Vhuile

Mpapier = 0.1 * 0 .85 (Kg /L) * 1.5 L = 141 g.

The paper specimens, measuring 81 x 81 mm^2, were subjected to aging within vessels that were not sealed (Figure 3). To simulate the impact of metallic elements within the transformer, metallic catalysts (zinc, copper, and aluminium of 1 g/l each) were placed onto a filter paper and then immersed in the oil. In order to replicate the respiration process in unenclosed breathing power transformers, receptacles were positioned within a metallic enclosure including an aperture that was filled with silica gel to impede the ingress of ambient moisture. The paper specimens were carefully immersed in beakers filled with a volume of 2 litres of oil. The entirety of the system was subjected to a temperature of 115°C within the oven. The specimens underwent a heating process for 500 hours [11].

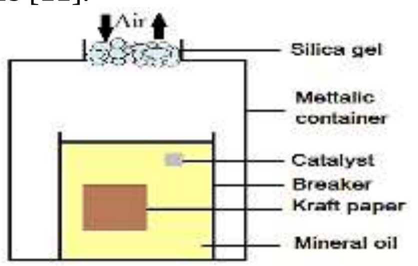


Fig. 3 Schematic representation of aging vessel.

Measurements were performed for aged pressboard and aged Kraft paper. For both papers, at different temperatures ranging from 40°C to 100°C and frequency range from 0,01Hz to 1000Hz.

IV. Results and Discussion

We divided the frequency into two ranges: from 0.01 Hz to 1 Hz denoting the low frequencies, and from 1 Hz to 1000 Hz representing the high frequencies. The results are plotted in decimal-log scale.

A. *Effect of temperature on loss factor*

Fig. 4 and Fig. 5 shows the behaviour of the loss factor of pressboard and kraft papers as a function of frequency for different temperatures. We observe that the loss factor decreases with the frequency and increases with the temperature. The loss factor of two papers declines dramatically with the rise of frequency in the low frequency band. Then starts to decrease more slowly with the frequency. In addition, the loss factor value and the effect of temperature tend to disappear at frequencies greater than 1000 Hz. Further, the loss factor of kraft paper was greater compared to pressboard. For the Kraft paper. Fig. 5 shows that the loss factor decreases for the temperature greater than 80°C.

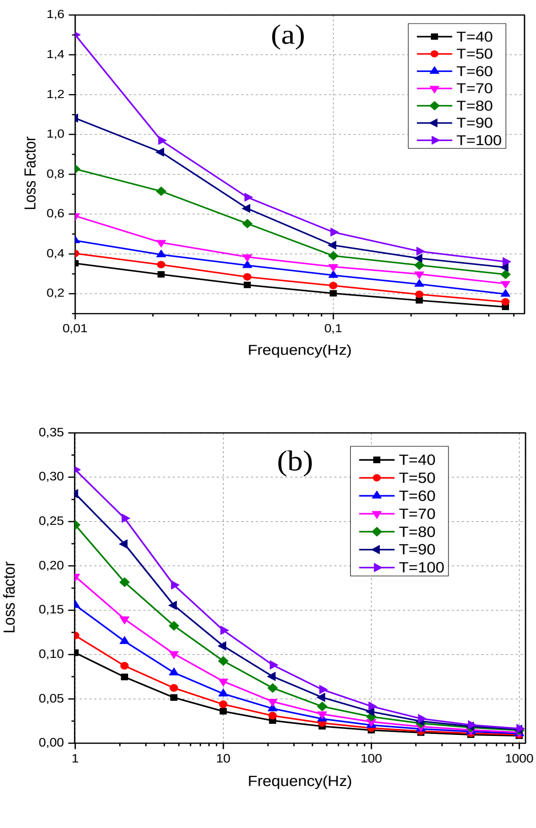


Fig. 4 Loss factor of pressboard as function of the frequency for different temperatures (a) low frequency (b) high frequency

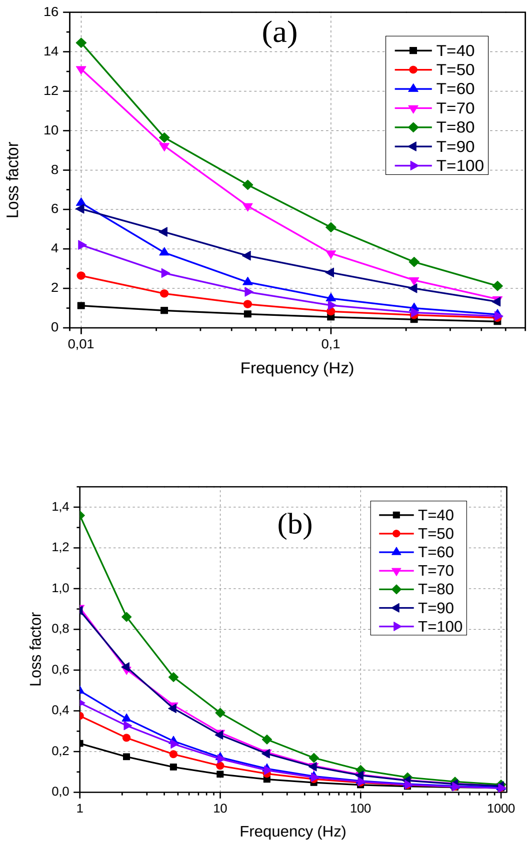


Fig. 5 Loss factor of kraft as function of the frequency for different temperatures (a) low frequency (b) high frequency

B. *Effect of aging on loss factor*

Fig. 6 and Fig. 7 shows the variation of loss factor of aged pressboard and aged kraft papers as a function of frequency for different temperature. The result revealed that the aging of papers contributes to an increase on the values of the loss factor for both papers. This rise can be attributed to the deterioration of the paper and aging process, resulting in the formation of moisture and low molecular weight acids. The observed rise in the loss factor of kraft paper within the frequency range of 0.01–1 Hz can be attributed primarily to the increased conductivity of the oil, which is a result of the presence of these by-products.

Furthermore, it can be seen that the loss factor increases with aging. The tanδ exhibits an increase in value as the temperature rises. For the samples characterized by aging increase becomes higher than for new samples. For aged insulation, the primary factor influencing the impact of insulation is the decrease in oil viscosity with increasing temperature. When the viscosity of oil decreases, the ionic mobility inside the oil increases, resulting an increase in dielectric loss.

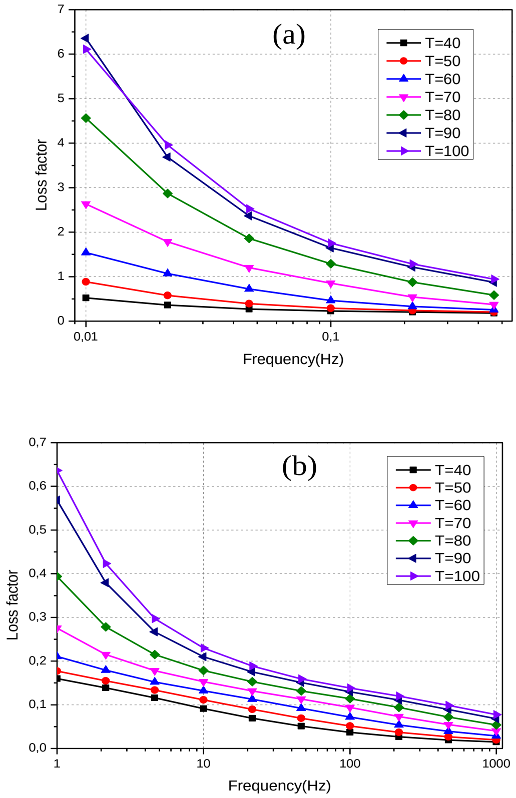
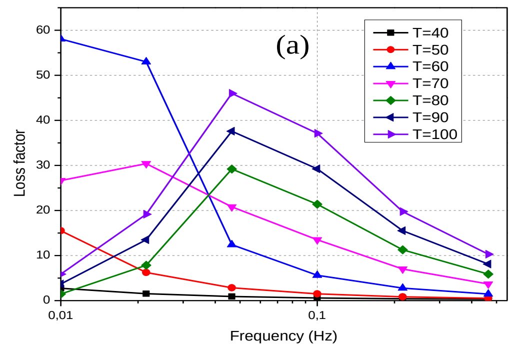


Fig. 6 Loss factor of aged pressboard as function of the frequency for different temperatures (a) low frequency (b) high frequency



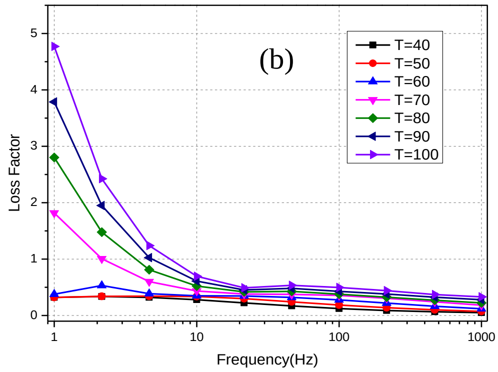


Fig. 7 Loss factor of aged kraft as function of the frequency for different temperatures (a) low frequency (b) high frequency

In addition, as the insulation ages and undergoes further degradation, more impurities appear, leading to further elevation of oil conductivity, particularly at higher temperatures. Consequently, the increase of dielectric loss becomes higher.

From Fig. 8 and Fig. 9 we note that the loss factor value of the pressboard was less than the kraft paper, whether in new or aged state. When the temperature rises to the point where the distance travelled by ions becomes smaller than the space within the paper pores, This leads to an increase in ion velocity up to a specific value, the Garton effect will appear in the insulation, tanδ exhibits a decrease at temperature 80°C due to Garton effect, as shown in Fig. 8.

Also, It is obvious that the value of the loss factor was marginal in the high-frequency range for all groups of samples.

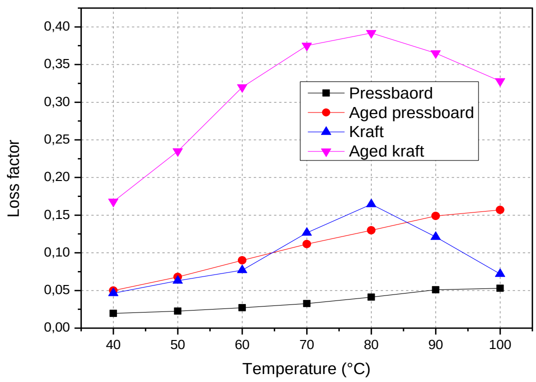


Fig. 8. Comparison of loss factor of papers at 50Hz as function of temperature

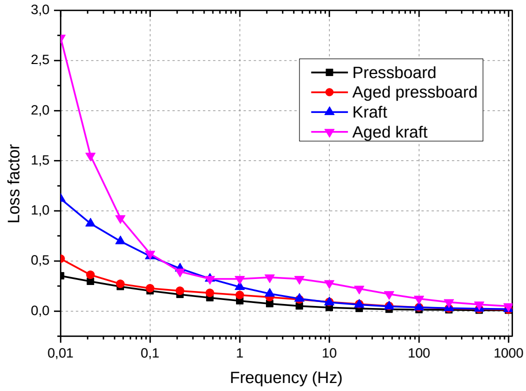


Fig. 9. Comparison of loss factor of papers at 40°C as function of different frequency

V. CONCLUSION

This study investigates the effect of temperature, aging, and frequency on the loss factor response of kraft and pressboard paper. Based on the FDS results obtained, it is evident that there is a significant correlation between these factors. Consequently, the following specific conclusions can be inferred :

The loss factor exhibited a direct correlation with frequency and temperature, decreasing with frequency and increasing with temperature.

The loss factor showed a rise as the papers undergoes the aging process.

Pressboard paper exhibited a lower loss factor compared to kraft paper, indicating that the aging process of kraft paper is more expedited.

The loss factor is inversely proportional to frequencies, where it increases at low frequencies and decreases at high frequencies, the variation was marginal in this range.

This paper indicated that the frequency domain spectroscopy method is an efficient tool to evaluate and predict the state of the oil-impregnated paper insulation.

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