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Moisture effect on the dielectric response of improved insulating papers impregnated with mineral oil

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Abstract. The electrical insulation system, usually composed of cellulosic materials and mineral oil, is essential for the reliable operation of the power transformers. The dielectric system must be kept in prime condition to increase the lifetime of the machine. Moisture in these materials reduces the dielectric strength and enhances the rate of insulation ageing. Frequency Domain Spectroscopy (FDS) is a promising method to analyse the effect of moisture in oil-paper insulation system. This study compares the influence of moisture on the dielectric capacity of 3 insulating papers; Diamond Printed Enhanced (DPE), Kraft and Thermally Upgraded Kraft (TUK) impregnated with mineral oil using FDS. The samples were prepared in the laboratory with different moisture content within 1% to 5%. Measurements were performed over a wide frequency range from 16.62 mHz to 5 kHz. It was found that the dielectric magnitudes measured on the DPE paper samples are higher compared to the other two types of paper samples and that the dielectric response is adversely affected by moisture content, regardless of the type of paper.

Key words. Dielectric response, FDS, insulating papers, mineral oil, moisture.

1. Introduction

In recent years, significant changes have taken place in the electrical system, primarily related to power generation from renewable sources. This has presented a challenge for the proper functioning of power transformers, which are essential for ensuring a secure electricity supply.

For instance, in wind power generation, transformers are subjected to frequent stops and starts, increasing electrical stress on these devices, as well as vibrations, which affect mechanical stability, [1]. These factors, along with moisture and temperature, can lead to significant degradation of the dielectric insulation system of these machines, typically composed of cellulose-based materials and mineral oil, thereby impacting their reliability and lifespan, [2]. Consequently, in recent years, new materials have been developed in pursuit of greater mechanical and electrical strength.

The dielectric response diagnostic method, due to non-destructive property, is widely used in the field of moisture assessment of oil-impregnated electrical equipment. In frequency domain, the dielectric response diagnostic method mainly used is Frequency Domain Spectroscopy (FDS), [3].

Several researchers have performed FDS studies using different types of pressboards impregnated with mineral oil at numerous moisture levels [2], [4], [5], [6]. Additionally, similar studies have been conducted using Kraft paper impregnated with mineral oil at various moisture levels, [3], [7], [8], [9]. All of them concluded that as humidity increases, there is a deterioration of the dielectric properties and a rise of the dielectric loss factor.

In this work, the state of the art has been expanded through the analysis of new improved insulating papers, Diamond Printed Enhanced (DPE) and Thermally Upgraded Kraft (TUK), for which there is no data in the bibliography.

2. Theoretical Background

To demonstrate the dielectric response principle, the process initiates with the application of an electric field E(t) onto a dielectric material, [10]. The material becomes polarized and, according to Maxwell equations, the current density is equal to (1).

$$J(t) = \sigma_0 E(t) + \frac{dD(t)}{dt} \tag{1}$$

Where: σ_0 is the DC conductivity of the dielectric material, D(t) is dielectric induction and J(t) is the current density. Rewriting (1) in frequency domain applying Fourier transform it will convert to (2).

$$J(\omega) = \sigma_0 E(\omega) + j\omega D(\omega) \tag{2}$$

Where: $\boldsymbol{\omega}$ is the angular frequency ($\boldsymbol{\omega = 2\pi f}$). Also, in the frequency domain D(t) is expressed as (3).

$$D(\omega) = \varepsilon_0 E(\omega) + P(\omega) \tag{3}$$

Where: P(ω) is polarization and is represented (4), and ε_0 is permittivity in the vacuum.

$$P(\omega) = \varepsilon_0[\varepsilon_\infty - 1 + \chi(\omega)]E(\omega) \quad (4)$$

Where: χ is susceptibility and ε_∞ is permittivity at infinite frequency. Using (3) and (4) in (2), the current density can be formulated as shown in (5).

$$J(\omega) = j\omega\varepsilon_0\left\{\varepsilon_\infty + \chi'(\omega) - j\left[\frac{\sigma_0}{\varepsilon_0\omega} + \chi''(\omega)\right]\right\}E(\omega) \quad (5)$$

An alternative expression for (5) is presented in (6).

$$J(\omega) = j\omega\varepsilon_0\{\varepsilon'(\omega) - j\varepsilon''(\omega)\}E(\omega) \quad (6)$$

Where: ε'(ω) is the real part of the complex permittivity ε(ω) and ε''(ω) is the imaginary part of the complex. The effects of moisture content, aging effects, and temperature in the insulation system of the power transformer will change ε' and ε'' in the different frequency range, [10]. The Dielectric Dissipation Factor (tan δ), whose formula is shown in (7), represents the dielectric loss, when the dissipation factor is higher the electrical losses increase.

$$tan\delta = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} \quad (7)$$

3. Experimental Procedure

A. Materials

Weidmann insulating papers, supplied by TMG Solutions, were analysed in this study. Their main properties are collected in Table I, [11], [12]. These papers were impregnated with a mineral oil, whose properties, as provided by the manufacturer, are shown in Table II.

Table I.- Properties of insulating papers

Property	Kraft	TUK	DPE
Apparent Density (g/cm³)	1.1	1.0	0.9-1.1
Tensile strength unfolded (MPa)	94	115	100
Elongation unfolded (%)	1.7	2.0	1.5
Moisture content (%)	< 8	< 8	3-5
Ash content (%)	0.3	0.3	0.75
Conductivity of aqueous extract (mS/m)	2.0	2.2	-
Electric strength in air unfolded (kV/mm)	10	10	-
Electric strength in oil (kV/mm)	70	70	73

Table II.- Properties of mineral oil

Property	Method	Value
Kinematic viscosity at 40°C (cst)	ASTM D445	9.98
Density at 20°C (g/mL)	ASTM D4052	0.839
Flash Point (°C)	ASTM D92	176
Pour Point (°C)	ASTM97	-48
Breakdown Voltage (kV)	UNE EN 60156	46
Dielectric loss factor at 90°C	UNE EN 60247	0.00198
Acidity (mg KOH/g)	IEC 61125C	0.42
Interfacial tension (mN/m)	ASTM D 971	43

B. Samples Preparation

The experimental procedure is based on four steps: drying, moistening, impregnation, and dielectric measurement, as has been done in previous studies, [3], [8], [9]. A set of paper specimens with thickness of 76 µm were cut to sizes of 69x860 mm. Then, the samples were rolled onto the test cell holder to a thickness of 1 mm. Before impregnation, paper specimens were dried in an oven (Memmert UF110) at 105ºC for 10 hours. Subsequently, the samples were tempered in vacuum and exposed to laboratory conditions (24º ± 0.8 ºC and 36.5 ± 2.5% humidity). The moisture content of the samples was determined according to equation (8) by controlling the mass during the atmosphere exposure.

$$Moisture\ (\%) = \frac{m_{wet} - m_{dry}}{m_{dry}} \cdot 100 \quad (8)$$

Complementary, oil samples drying was carried out at 70ºC in a vacuum chamber (Memmert V0 500) for 24 hours, with cycles of 4 hours in vacuum (65 mbar) and 1 hour in nitrogen (500 mbar). Afterward, they were placed in hermetically sealed bottles for 24 hours to cool down to room temperature. Then, the test cell, which already contained the paper, was filled with the oil. Subsequently, it was closed, and remained at rest for 2 hours to ensure the proper impregnation of the paper before measurement.

C. Measurement Setup

A three-electrode test cell, whose scheme is shown in Fig. 1, was used to analyse the dielectric response.

FDS was conducted on paper samples using OMICRON Lab's instrument, Spectano 100, applying 50V of peak voltage in a frequency range from 16.62 mHz to 5 kHz, [13]. Values of tan δ, ε' and ε'', and σ were obtained from this study.

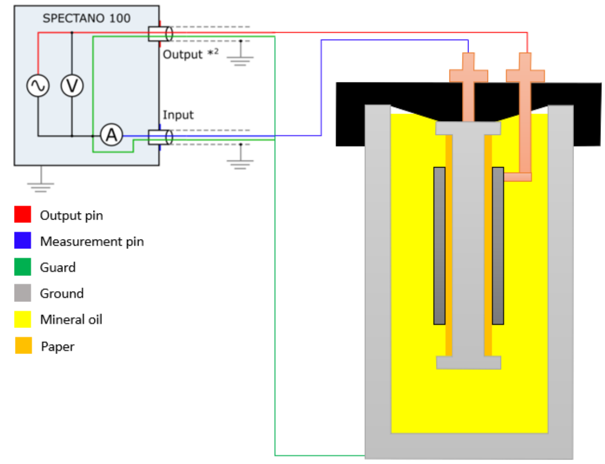

Fig. 1. Test cell connection diagram

4. Results and discussion

A. Samples moisture content

Moisture contents in tests with DPE, TUK and Kraft papers impregnated with mineral oil are collected in Table III, Table IV and Table V, respectively.

As can be observed, oil's moisture content does not exhibit significant variations over the course of time during each measurement. Additionally, the moisture levels of the paper and mineral oil samples remain remarkably similar in each case.

Table III.- DPE Paper samples impregnated with mineral oil

Paper's moisture before impregnation (%)	*Oil's moisture before dielectric measurement (ppm)*	*Oil's moisture after dielectric measurement (ppm)*
1.09%	21.9	25.2
2.97%	19.9	24.7
5.05%	21.2	25.5

Table IV.- Kraft paper samples impregnated with mineral oil

Paper's moisture before impregnation (%)	*Oil's moisture before dielectric measurement (ppm)*	*Oil's moisture after dielectric measurement (ppm)*
0.97%	20.9	23.1
3.04%	22.5	25.3
5.04%	23.4	26.8

Table V.- TUK paper samples impregnated with mineral oil

Paper's moisture before impregnation (%)	*Oil's moisture before dielectric measurement (ppm)*	*Oil's moisture after dielectric measurement (ppm)*
0.96%	19.9	22.7
3.02%	20.4	23.1
4.98%	20.2	23.9

B. Dielectric behavior

1) Dielectric response of oil impregnated paper samples with low moisture level

Fig. 2 shows the tan δ of mineral oil impregnated DPE, TUK and Kraft paper samples with approximately 1% moisture content (m.c.).

In Fig. 2, it can be observed that the highest tan δ is associated with DPE paper across the entire frequency range. In the case of TUK, it remains superior to Kraft up to 25 Hz; beyond this point, Kraft surpasses it. Additionally, the general shape remains nearly the same for each paper. At 50 Hz, the tan δ of DPE paper is 218% higher than that of Kraft paper, while for TUK paper, it is 121% higher.

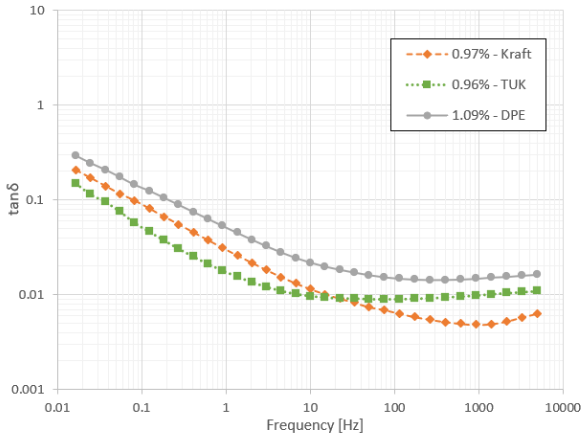

Fig. 2. Comparative of tan δ of samples with 1% m. c.

Fig. 3 shows the ε' of mineral oil impregnated DPE, TUK and Kraft paper samples with approximately 1% m. c.

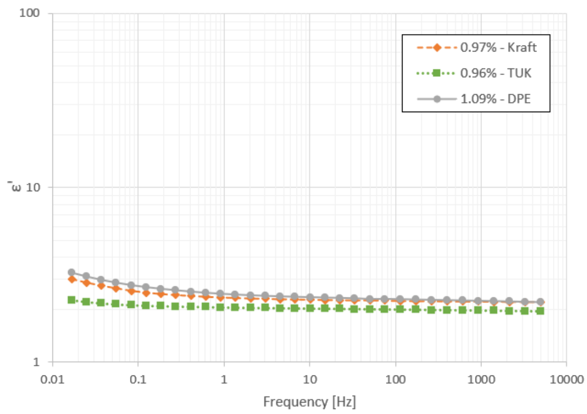

Fig. 3. Comparative of ε' of samples with 1% m. c.

It is observed that ε' remains nearly constant for frequencies exceeding 1 Hz. As can be seen in Fig. 3, DPE paper has the highest ε', at 50 Hz is 114% higher than TUK, then Kraft is the second highest, at 50 Hz is 113% higher, and TUK has the lowest ε'.

Fig. 4 shows the σ of mineral oil impregnated DPE, TUK and Kraft paper samples with approximately 1% m. c.

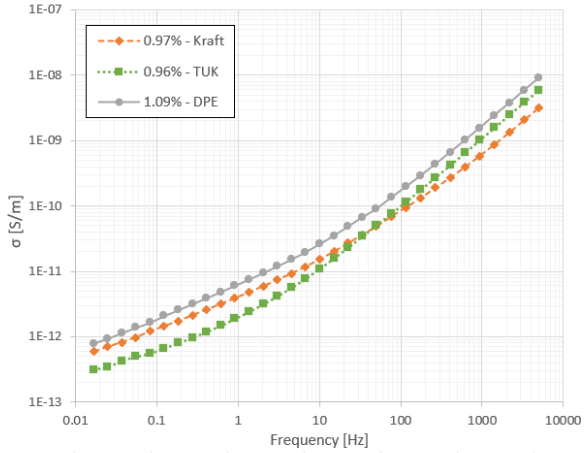

Fig. 4. Comparative of σ of samples with 1% m. c.

As observed in Fig. 4, there is a steady reduction of conductivity as frequency decreases. The influence of the paper type employed affects a similar effect on conductivity when compared to the tan δ.

2) Dielectric response of oil impregnated paper samples with medium moisture level

Fig. 5 shows the tan δ of mineral oil impregnated DPE, TUK and Kraft paper samples with approximately 3% m.c.

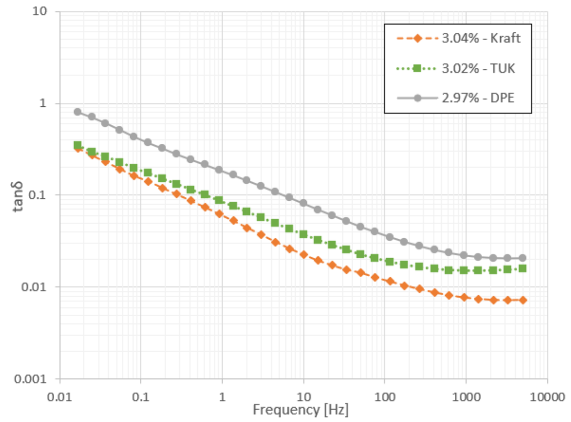

Fig. 5. Comparative of tan δ of samples with 3% m. c.

Comparing Fig. 5 with Fig. 2, it can be seen that the highest tan δ is still associated with the DPE paper, being 316% higher than Kraft paper at 50 Hz. However, in this case, TUK paper has a higher tan δ than Kraft paper across the entire frequency range, being 157% higher at 50 Hz.

Fig. 6 shows the ε' of mineral oil impregnated DPE, TUK and Kraft paper samples with approximately 3% m. c.

Comparing Fig. 6 with Fig. 3, ε' remains nearly constant for frequencies higher than 50 Hz. In Fig. 6, it can be seen that DPE paper has the highest ε', at 50 Hz is 113% higher than TUK, but Kraft remains superior to TUK up to 0.15 Hz; beyond this point, TUK surpasses Kraft, being 107% higher at 50 Hz.

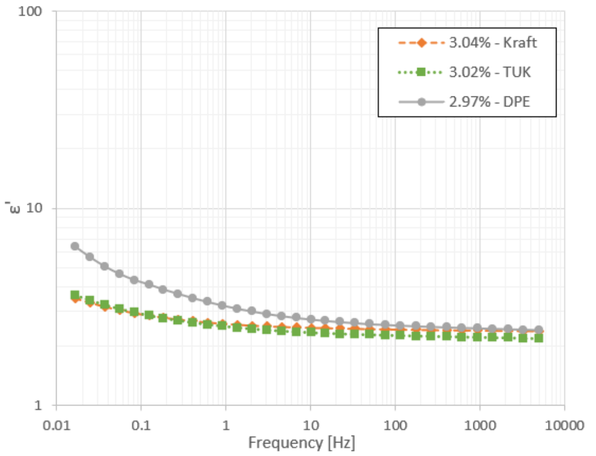

Fig. 6. Comparative of ε' of samples with 3% m. c.

Fig. 7 shows the σ of mineral oil impregnated DPE, TUK and Kraft paper samples with approximately 3% m. c.

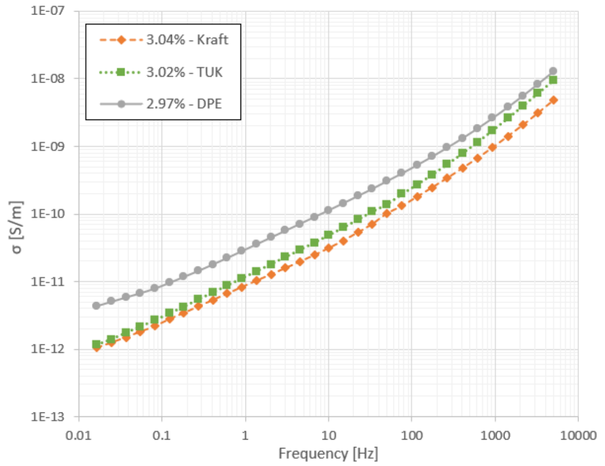

Fig. 7. Comparative of σ of samples with 3% m. c.

As observed in Fig. 7, conductivity presents a similar behavior at 3% m.c. as at 1% m.c., with is a steady reduction of conductivity as frequency decreases. However, in Fig. 7, DPE paper exhibits the highest σ across the entire frequency range; at 50 Hz is 307% higher than Kraft, while for TUK paper, it is 137% higher.

3) Dielectric response of oil impregnated paper samples with high moisture level

Fig. 8 shows the tan δ of mineral oil impregnated DPE, TUK and Kraft paper samples with approximately 5% m.c.

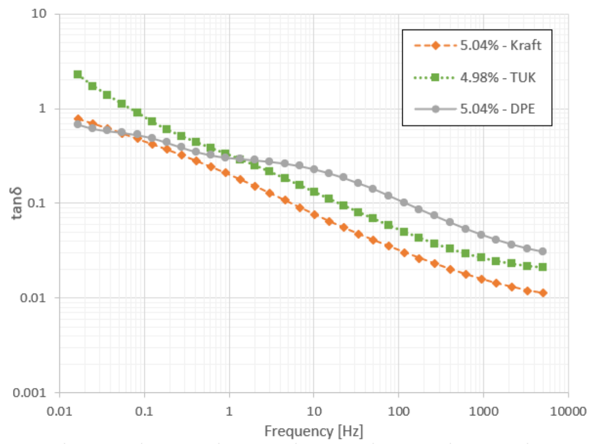

Fig. 8. Comparative of tan δ of samples with 5% m. c.

In Fig. 8, it is observed that DPE has the highest tan δ for frequencies higher than 1 Hz, after which TUK and Kraft surpass it. This behavior differs from that observed in Fig. 2 and Fig. 5. This effect may be attributed to the resin printed on this type of paper. At 50 Hz, the tan δ of DPE paper is 348% higher than that of Kraft paper, while for TUK paper, it is 168% higher.

Fig. 9 shows the real part of the complex permittivity of mineral oil impregnated DPE, TUK and Kraft paper samples with approximately 5% m. c.

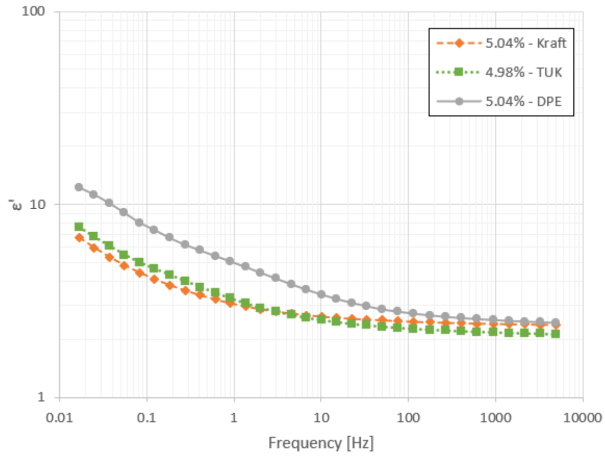

Fig. 9. Comparative of ε' of samples with 5% m. c.

Comparing Fig. 9 with Fig. 3 and Fig. 6, ε' remains nearly constant for frequencies higher than 100 Hz. In Fig. 9, DPE paper has the highest ε', but Kraft paper remains superior to TUK paper up to 4 Hz; beyond this point, TUK surpasses Kraft. As moisture increases, the real part of complex permittivity of TUK paper starts to be higher than the one of Kraft paper at higher frequencies.

Fig. 10 shows the conductivity of mineral oil impregnated DPE, TUK and Kraft paper samples with approximately 5% m. c.

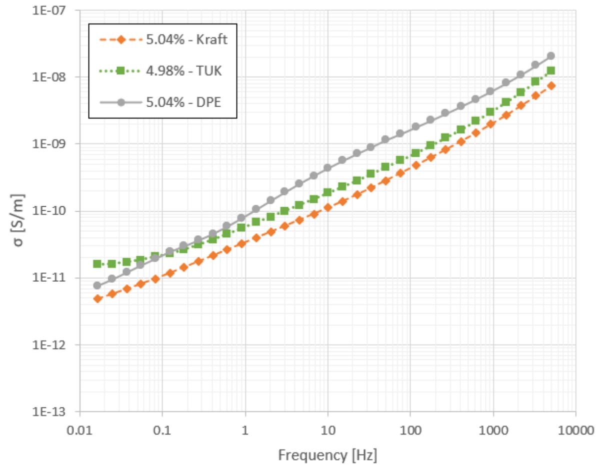

Fig. 10. Comparative of σ of samples with 5% m. c.

As observed in Fig. 10, conductivity presents a similar behavior at 5% m. c. compared to 1% and 3% m. c. There is a steady reduction in conductivity as frequency decreases. However, in Fig. 7, DPE paper has the highest σ up to 25 Hz; beyond this point, TUK paper surpasses it. Kraft paper remains the lowest across the entire frequency range.

For all types of paper samples impregnated with mineral oil, the values of tan δ, ε', and σ exhibit higher magnitudes in the scenario with a 5% m.c. when contrasted with the cases of 3% and 1% m.c.

To clearly observe this behavior, Fig. 10, Fig. 11 and Fig. 12 show the values of tan δ, ε', and σ of Kraft paper samples impregnated with mineral oil at different moisture levels.

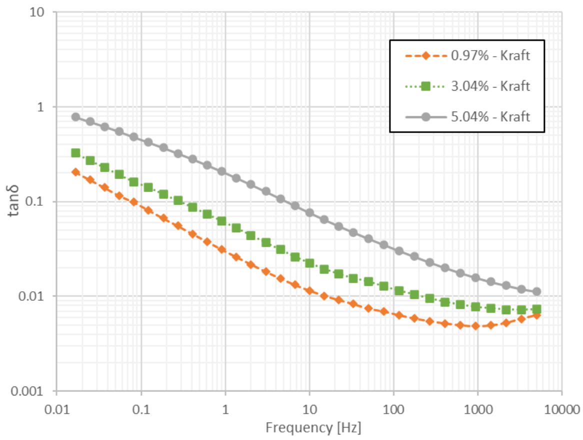

Fig. 11. Tan δ of Kraft paper samples with different m.c.

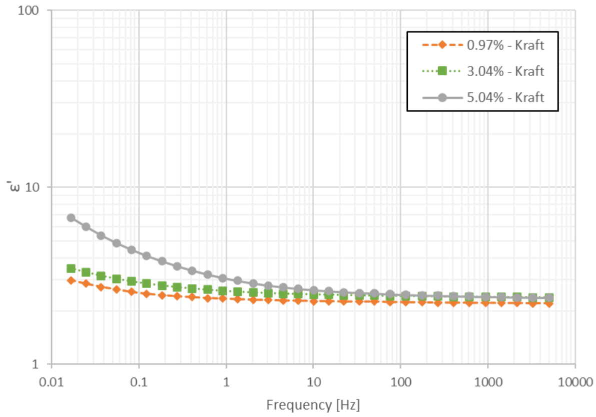

Fig. 12. ε' of Kraft paper samples with different m.c..

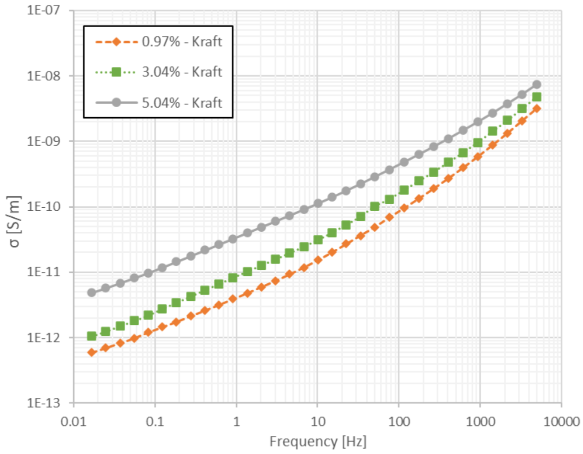

Fig. 13. σ of Kraft paper samples with different m.c.

All papers impregnated with mineral oil exhibit a similar behavior when moisture increases: there is a deterioration of the dielectric properties and a rise of the dielectric loss factor. The presence of moisture exerts an influence on the electrical polarization within dielectric insulation, thereby causing variations in the dielectric response. The introduction of moisture in the paper leads to a reduction in its resistivity, resulting in an increase of both conductivity and tan δ, [14].

The DPE samples exhibit higher values of tan δ, ε', and σ compared to TUK and Kraft samples. As shown in [15], DPE paper also has a higher tan δ in the case of impregnation with mineral oil for different degrees of aging. This behavior could be related to the manufacturing process of this type of paper, as it involves the printing of resin on its surface.

5. Conclusion

In this study, the effect of moisture on the dielectric response of DPE, TUK and Kraft paper samples impregnated with mineral oil was investigated using FDS measurements.

It was found that the dielectric capacity decreases with the increase of the paper's moisture content, which is reflected in a higher values of tan δ and conductivity.

Moreover, it was observed that DPE paper samples exhibit the highest values of tan δ, ε', and σ compared to TUK and Kraft samples, for the entire range of moisture values analysed.

The moisture data of the paper samples covers a wide range, enabling the assessment of dielectric response from the initial dry conditions of the transformer to necessary insulation re-drying due to high moisture. Experimental values are expected to have practical utility as a result.

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