# Experimental Evaluation of the Moisture Effect on the Dielectric Properties of Thermally Upgraded Kraft Paper Impregnated with Mineral Oil and Natural Ester

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***Abstract*— An essential component of power transformers is the electrical insulation system, composed of cellulose-based materials and usually mineral oil. Currently, this fluid is being replaced by alternative dielectric fluids derived from plants, such as soybean, sunflower, etc. The dielectric system must be kept in prime condition. Moisture affects the dielectric strength and the rate of insulation ageing. Frequency Domain Spectroscopy (FDS) is a promising method to analyze the moisture effect in oil-paper insulation system of the transformer. This study investigates the influence of moisture on the dielectric behavior of Thermally Upgraded Kraft (TUK) paper, both non-impregnated and impregnated with mineral oil and soybean ester. 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 impregnation of the paper samples helps to reduce the variation of tan δ with the incrementation of moisture and that the dielectric response is sensitive to moisture content regardless of the impregnation and the type of impregnation liquid.**

***Keywords*— Biodegradable, dielectric response, FDS, moisture, TUK paper, mineral oil, natural ester.***

## I. Introduction

Ensuring the reliability of power transformers is essential for the effective operation of power systems, [1].The insulation of this machines is mainly composed of cellulose-based materials, such as paper and pressboard, and insulating oil. Nowadays, mineral oil is the most used dielectric fluid, due to its low cost and good dielectric performance. Nevertheless, this liquid has a very low ignition temperature and biodegradability. Concerning human health and the environment, efforts have been made for the development of environmentally friendly vegetable esters as an alternative to conventional mineral oil, [2].

The lifespan of the power transformer depends on the degradation of the solid insulation, which is strongly affected by moisture and temperature, [3]. The degradation of this material reduces its dielectric performance, which is critical for the reliable operation of the transformers, [4]. Because of that, non-destructive methods, as FDS, are commonly used for the diagnosis of theses, [5].

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In this work, the main dielectric properties of a TUK paper have been studied through FDS. The analysis includes the effect of the moisture content (m. c.) and the impregnation fluid in the insulating performance.

## II. Experimental Procedure

### *A. Materials*

First, Table I shows the physicochemical properties of the paper used for the tests. WEIDMANN insulating papers were supplied by TMG Solutions, [6].

TABLE I. PHYSICOCHEMICAL PROPERTIES OF TUK PAPER

| **Property** | **Value** |
|---|---|
| Apparent Density (g/cm$^3$) | 1.0 |
| Tensile strength unfolded (MPa) | 115 |
| Elongation unfolded (%) | 2.0 |
| Moisture content (%) | < 8 |
| Ash content (%) | 0.3 |
| Conductivity of aqueous extract (mS/m) | 2.2 |
| Electric strength in air unfolded (kV/mm) | 10 |
| Electric strength in oil (kV/mm) | 70 |

In addition, mineral oil and soybean ester were used to impregnate the paper. Table II shows the main properties of these fluids, supplied by the manufacturers.

TABLE II. PHYSICOCHEMICAL PROPERTIES OF MINERAL OIL AND SOYBEAN ESTER

| **Property** | **Mineral Oil** | **Soybean Ester** |
|---|---|---|
| Density at 20°C (g/mL) | 0.839 | 0.92 |
| Kinematic viscosity at 40°C (mm$^2$/s) | 9.98 | 32-34 |
| Flash Point (°C) | 176 | 320 |
| Pour Point (°C) | -48 | -18 |
| Breakdown Voltage (kV) | 46 | > 55 |
| Dielectric loss factor at 90°C | 0.00198 | 0.1 |
| Acidity (mg KOH/g) | < 0.01 | < 0.05 |

### *B. Samples Preparation*

A set of paper specimens with 76 µm thickness were cut to sizes of 69x860 mm. Then the samples were rolled to the specimen holder to a thickness of 1 mm. Before impregnation, paper specimens were dried in an oven (Memmert UF110) at

105 ºC for 10 hours. Then the samples were tempered in vacuum and exposed to laboratory conditions (24º ± 0.8 ºC and 36.5 ± 2.5% humidity). Moisture of the samples was determined according to (1), controlling the mass during the atmosphere exposure. For the non-impregnated samples, once the desired moisture content was achieved, the test cell was vacuumed, and the dielectric measurement was carried out.

$$Moisture\ (\%) = \frac{m_{wet} - m_{dry}}{m_{dry}} \cdot 100 \qquad (1)$$

Complementary, dielectric fluids were dried at 70 ºC in a vacuum chamber (Memmert V0 500) for 24 hours in cycles of 4 hours in vacuum (65 mbar) and 1 hour in nitrogen (500 mbar). After that, the samples were placed in hermetically sealed bottles for 24 hours to cool down to room temperature. Then, they were introduced into the measuring cell with the paper samples. Subsequently, the test cell was closed, and the cell remained at rest for 2 hours to ensure the proper impregnation of the paper before starting the dielectric measurement.

### C. *Measurement Setup*

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

FDS was conducted on paper samples by using OMICRON Lab's instrument, Spectano 100, in the frequency range from 16.62 mHz to 5 kHz and with a 50 V voltage, [7]. Complex permittivity (ε' and ε''), dielectric dissipation factor (tan δ), and conductivity (σ) were obtained from this study.

## III. Results and Discussion

### A. *Samples Moisture Content*

The moisture content of the TUK paper (%) and of the dielectric fluids (ppm) during the measurements is collected in Table III. As can be observed, soybean ester's moisture content is almost 3 times higher than mineral oil's moisture content.

Despite the difference in moisture content among the dielectric liquids, the moisture level in non-impregnated paper samples and those impregnated with mineral oil and natural ester remains remarkably similar. For this reason, the results obtained in this study can be compared.

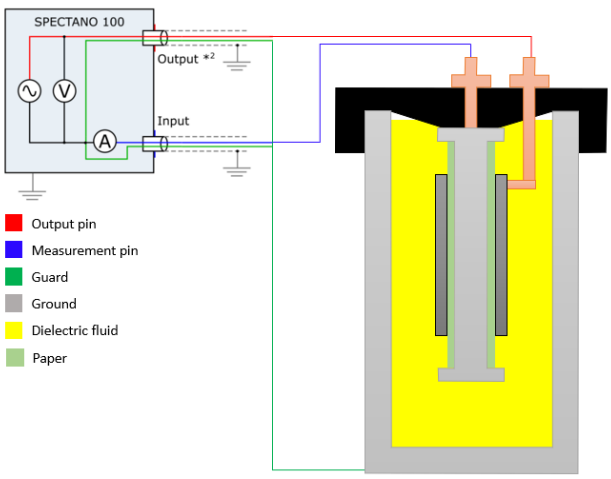


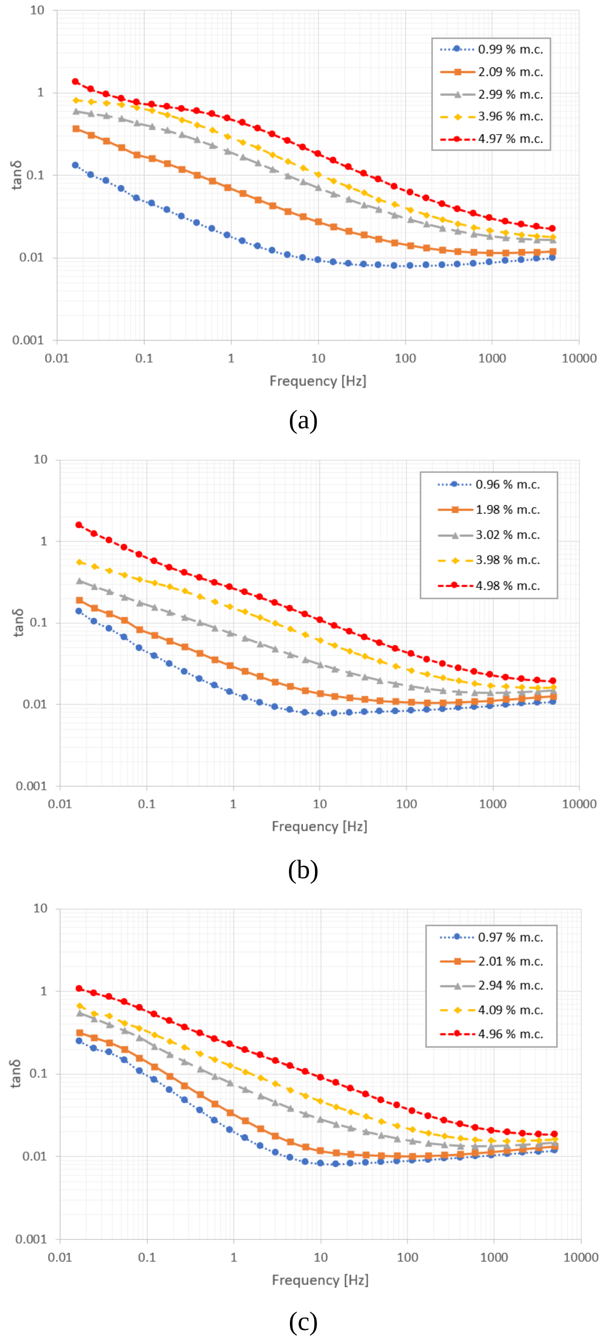

Fig. 1. Test cell connection diagram

TABLE III. Moisture Content of Paper Samples and Fluids

| Non-Impregnated | Impregnated with mineral oil | Impregnated with soybean ester |
|---|---|---|
| 0.99% | 0.96% (21.2 ppm) | 0.97% (60.7 ppm) |
| 2.09% | 1.98% (19.3 ppm) | 2.01% (62.5 ppm) |
| 2.99% | 3.02% (20.5 ppm) | 2.94% (58.8 ppm) |
| 3.96% | 3.98% (18.8 ppm) | 4.09% (64.1 ppm) |
| 4.97% | 4.98% (22.0 ppm) | 4.96% (67.2 ppm) |

### B. *Dielectric Behavior*

Fig. 2 shows the tan δ of both non impregnated and impregnated paper samples.




(a)

(b)

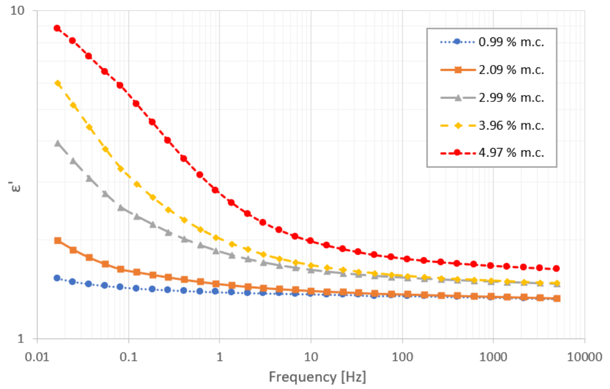
(c)

Fig. 2. Comparative of tan δ of (a) non-impregnated samples and samples impregnated with (b) mineral oil and (c) soybean ester

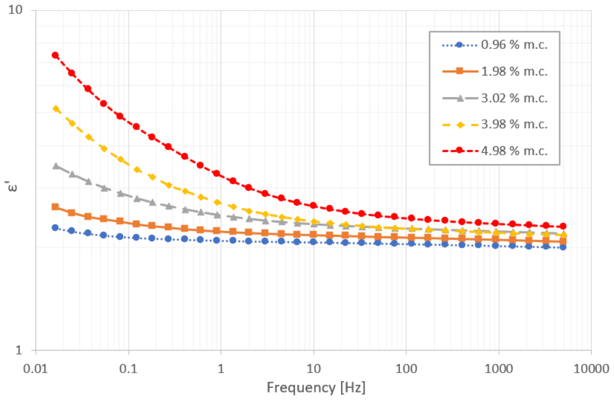
It can be clearly seen in that moisture significantly impacts the dielectric response, inducing a substantial upward magnitude shift in the entire dielectric response. However, the general shape of dielectric measurements remains nearly the same with increasing moisture level.

It is also noteworthy that non-impregnated samples exhibit higher values of tan δ than those impregnated with mineral oil and soybean ester for the same moisture content. At 50 Hz, the tan δ at 5% m. c. for non-impregnated samples is 11 times higher compared to 1%. Also at 50 Hz, the tan δ of samples impregnated with mineral oil and soybean ester, it is 7 and 5.5 times higher, respectively, compared to 1%.

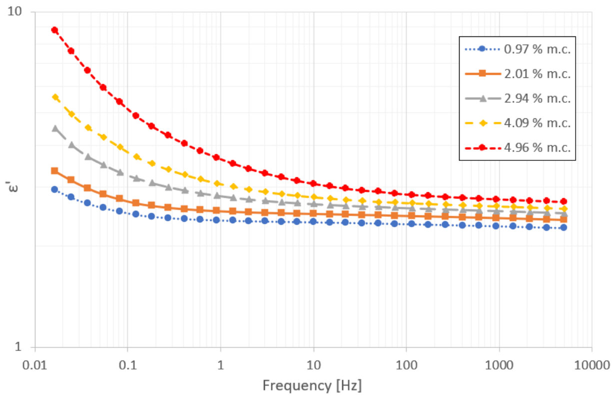
Moreover, Fig. 3 shows the ε’ of both non-impregnated and impregnated paper samples.




(a)




(b)

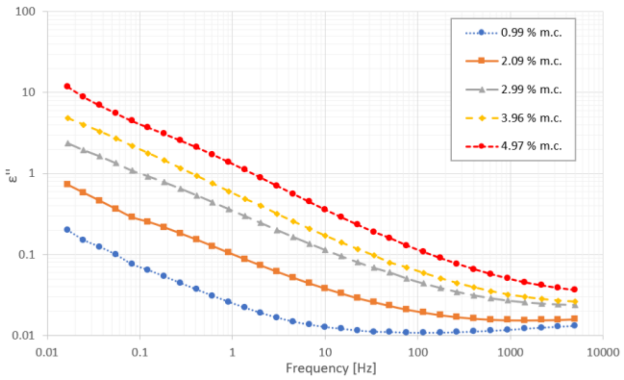



(c)

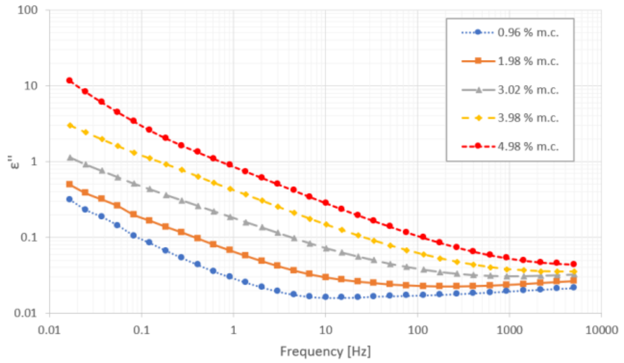
Fig. 3. Comparative of ε’ of (a) non-impregnated samples and samples impregnated with (b) mineral oil and (c) soybean ester.

It is observed that ε’ remains nearly constant for frequencies exceeding 10 Hz and the presence of moisture mainly influences the low-frequency part of the response. This behavior can be also observed in [8] and [9].

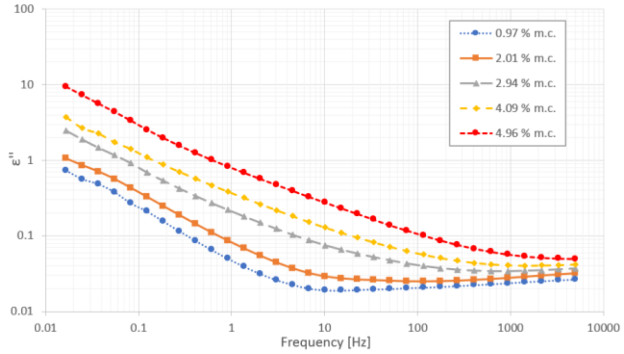
Then, Fig. 4 shows the ε’’ of both non-impregnated and impregnated paper samples.




(a)




(b)




(c)

Fig. 4. Comparative of ε’’ of (a) non-impregnated samples and samples impregnated with (b) mineral oil and (c) soybean ester.

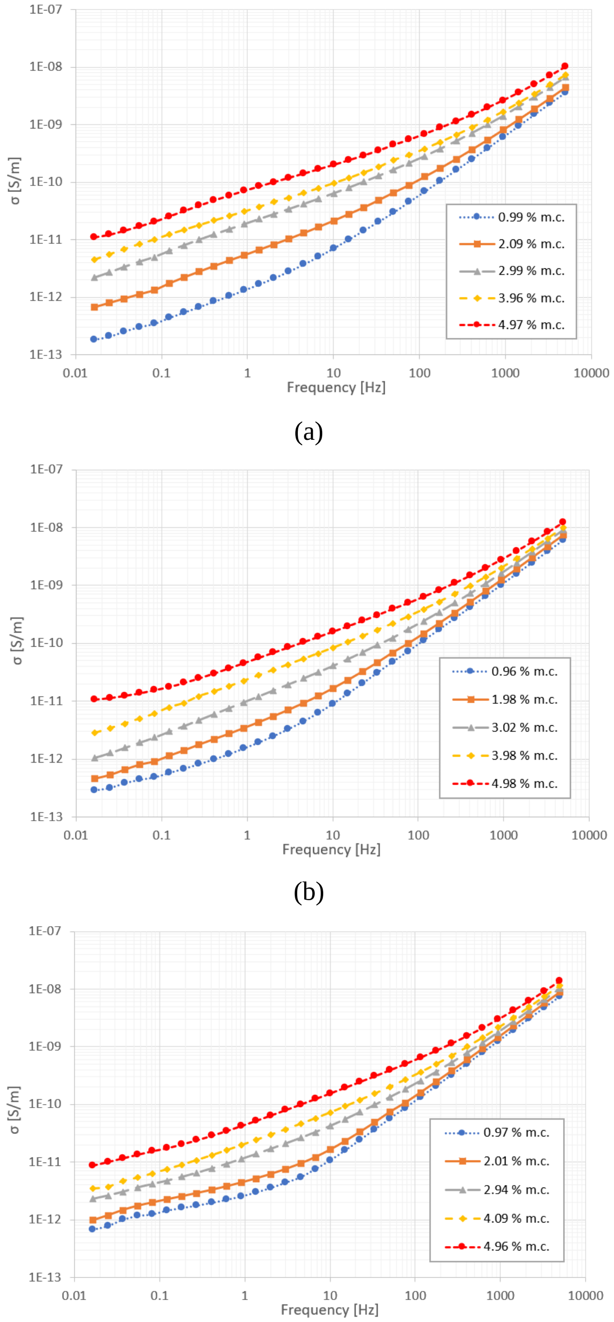
It can be clearly seen that moisture has a bigger influence on ε" than on ε'. However, the general shape of ε" remains nearly same with increasing moisture level, as is the case with the tan δ.

Even though the measurement cell and procedure employed in [1], [8], and [10] differ from those presented in this study, the values and trends of tan δ and ε" are similar to those observed in these articles.

Finally, the conductivity of the samples is shown in Fig. 5. As can be observed, there is a steady reduction of conductivity as frequency decreases. Also, moisture influences the dielectric measurement by shifting the curves upward magnitude shift.

Non-impregnated samples and those impregnated exhibit a similar behavior when moisture increases: there is a deterioration of the dielectric properties and a rise of the tan δ.

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 augmentation of both conductivity and tan δ, [11].




(a)

(b)

(c)

Fig. 5. Comparative of σ of (a) non-impregnated samples and samples impregnated with (b) mineral oil and (c) soybean ester

## IV. Conclusion

In this study, the effect of moisture on the dielectric response of non-impregnated TUK paper samples and mineral oil and soybean ester impregnated samples was investigated by using FDS measurement.

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

Moreover, it was observed that the impregnation of the paper changes its dielectric behavior, reducing the tan δ, especially with the soybean ester. Also, it helps to substantially decrease the variation of tan δ with the moisture content.

The paper samples' moisture data covers a wide range, enabling 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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