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# Study on the contamination rate of mineral oil in natural-ester retrofilled transformers

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***Abstract*—The replacement of mineral oil by ester (retrofilling) is a practice used in power transformers to reduce fire and environmental risk. Although measures are taken to remove traces of oil on the paper, a certain amount of mineral oil remains, which migrates over time. This article presents a study to evaluate the migration of mineral oil from paper to ester using techniques such as the iodine value or the measurement of permittivity and dielectric losses.**

***Index Terms*—Natural ester, retrofilled transformer, dielectric response, relative permittivity, Kraft paper, oil-paper insulation, contamination rate, iodine index.**

## I. Introduction

TRANSFORMER retrofilling with natural or synthetic esters is becoming a widespread practice as a solution to comply with the fire safety or environmental regulations and to increase the life expectancy of the equipment. Ester insulating liquids are biodegradable and have fire points almost three times larger than those of mineral oils (MO). Moreover, esters are polar materials what increases their affinity for water providing a certain protection to the solid insulation [1]. Ester retrofilling of transformers that have been operated with MO requires a much less investment than replacing the equipment with new ester-filled units.

At present, there are no standard procedures for retrofilling a transformer, which operates with MO, with a natural or a synthetic ester. Ester's manufacturers have their own procedures that typically consist of four steps: draining the MO from the tank, dripping the MO from the active part, flushing the surface of the active part with hot ester and filling the tank with the new insulating liquid [2], [3].

Retrofilling procedures are designed to remove as much MO from the transformer as possible and it is to be expected that the remaining MO in the tank or core after completing the process will be small. Nevertheless, because of the nature of cellulose and oil, the geometry of transformer solid insulation and the physics of mass transport process, it is not possible to remove all the MO adsorbed in the solid insulation and, when a transformer is retrofilled with natural or synthetic ester, the solid insulation will remain impregnated with a certain amount MO.

This fact introduces some uncertainties that have not been studied in detail, such as, how the MO migration dynamics will be from the solid insulation to the ester once the transformer is back in service, what the characteristics of the MO-contaminated ester will be or how the fact of operating with a mixture of insulating liquids will affect the predictive maintenance tests results [2], [4].

There is no clear agreement on the amount of MO that remains in the different components of the transformer when it is retrofilled. Some authors give approximate data without reporting how they were obtained. McShane et al. [2] reported that the amount of residual MO is approximately 4-7% of the total liquid insulation volume after retrofilling; other authors such as Fofana [5], Toudja [6] and Zsanowski [7] raise the percentage to 10%, and Beroual [8] states that the residual volume of MO reaches 20% of the liquid insulation volume. Only Wang et al. [3] report the method used to estimate the contamination rate (i.e. the kinematic viscosity measurement) which was less than 3%. Some authors claim that there is a gradual movement of residual MO from cellulosic insulation towards liquid insulation of the transformer during the first six months after being on load [5], [9].

Not much research has been published on the topic of transformer retrofilling up to date. On the one hand the practice is still relatively new and it has been mainly developed by the transformer and insulating fluids industry which are not so prone to disseminating their results. Additionally, there is a difficulty on investigating the topic on experimental prototypes, since the studies require some chemical or electrical characterization of the test objects or fluids which is not sufficiently defined.

In this paper the retrofilling of a transformer with natural ester (NE) has been emulated by means of a laboratory prototype. The migration process of MO from cellulose to ester has been characterized by chemical and electrical measurements. The objective of the work is to get insight on the migration process of MO from the solid insulation to the ester once the transformer is in service and to quantify the rate of contamination of the NE with MO throughout the experiment. Additionally, the work investigates on the applicability of different methods to evaluate the migration process in real transformers.

## II. Prototype design

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## A. Test objects

In order to study the dynamics of the solid-liquid insulation system after retrofilling of a transformer, a prototype was designed which incorporates a coil with 8.5 layers of Kraft paper as solid insulation, up to a thickness 0.7 mm. The paper was wound around an aluminium core using a winding machine to ensure that the tightness of the paper in all the prepared specimens was the same.

The solid insulation was first impregnated with MO and then subjected to retrofilling with NE. As will be explained later, the solid insulation prototype was fitted into a vessel which contained NE as liquid insulation. Two additional insulation prototypes were prepared which were impregnated with MO and NE respectively and immersed in vessels with the same liquids used for impregnation, to serve as a reference for the behaviour of solid-liquid insulation systems of transformers which have not been subjected to retrofilling.

One of the objectives of the experiment was to determine how the dielectric response of the insulation changes as migration of MO between paper and NE progresses. To measure the dielectric response, a system of two electrodes is needed. The aforementioned aluminum core was used as ground electrode and an external electrode was placed on the surface of the paper. The external electrode was a metallic mesh with aperture size 0.75 x 0.75 made of stainless steel. The purpose of using a mesh is to provide an electrode that allows a reliable measure of the dielectric response of the paper while allowing the flow of MO through it. Several mesh electrodes were tested in a previous work [10] and the one selected for the described prototypes proved the best behaviour.

The capacitance, $C$, of a cylindrical capacitor is directly related to the relative permittivity ($\varepsilon_r$) of the dielectric material placed between the capacitor plates according to eq. 1.

$$C = \frac{2\pi\varepsilon_0\varepsilon_r L}{\ln(R_2/R_1)} \tag{1}$$

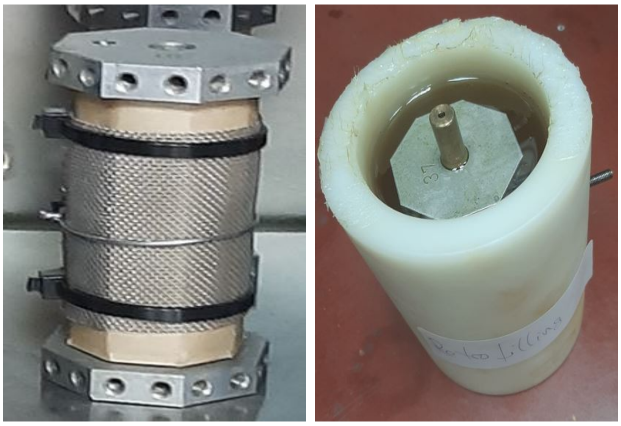
where $\varepsilon_0$ is the permittivity of the vacuum, $\varepsilon_r$ is the relative permittivity of the dielectric medium, $L$ is the height of the capacitor and $R_1$ and $R_2$ are the inner and outer radius of the cylindrical electrodes respectively.

One of the prototypes tested in this work is shown in Fig. 1a. During the experiments, the prototypes were fitted into a vessel made of Teflon and filled with insulating fluid (Fig. 1b).

Three test objects were characterized during this study: one of them simulating the insulation system of a MO filled transformer (MOFT), the second one simulating the insulation system of a NE filled transformer (NEFT) and, the last one, representing the insulation system of a transformer that was initially impregnated with MO and then retrofilled with NE (RFT). The oils used in this experiment were two commercial oils, an inhibited MO and a soybean-based NE.

## B. Impregnation process

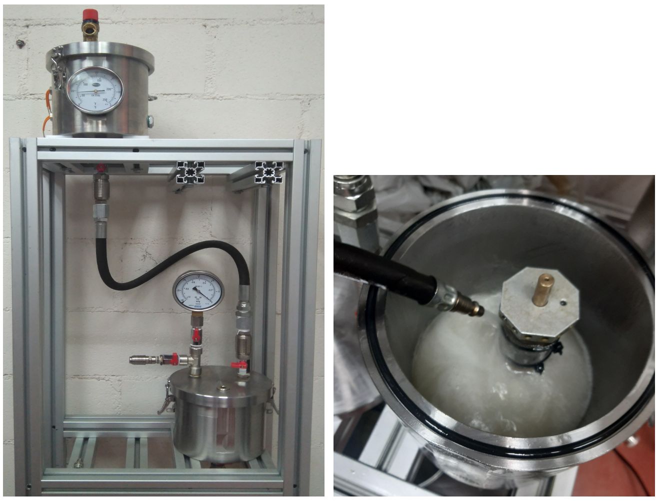
Each one of the three test objects was subjected to a different impregnation process: for the MOFT the Kraft paper was impregnated with MO, for the NEFT the paper was impregnated with NE. For the object that was used to emulate the retrofilled transformer, the paper was subjected to impregnation with MO and then, after flushing the paper surface with NE, it was placed into a vessel filled with NE.



(a) Insulation model (b) Vessel

Fig. 1. Test objects considered in the experimental study

The impregnation processes was performed under vacuum, applying a hot-oil-spray to the solid insulation, as is done in factory to impregnate the active part of real transformers. The impregnation plant shown in Fig. 2a was used to this aim.



(a) Impregnation plant (b) Flushing of the test object subjected to retrofilling.

Fig. 2. Impregnation of the test objects

To minimize the influence of moisture in the study, the test specimens were subjected to drying before impregnation. The drying process consisted of a 24 hours period of vacuum drying in an oven at 60ºC and 1 mbar followed by another period of 2 hours at 90ºC and 1 mbar. The fluids used for the impregnation were also subjected to drying, reaching moisture contents of 7 ppm for the MO and 146 ppm for the NE.

During the impregnation process, the upper chamber of the impregnation plant was filled with the insulating fluid used to impregnate the solid insulation. By means of a resistor, the liquid is heated to the desired temperature. In this case the impregnation temperature was 60ºC. The test object is placed in the bottom chamber and vacuum is applied by means of a pump at a pressure below 1 mbar. Once the temperature of the upper chamber was stable, the hosepipe that connects both chambers is filled and, subsequently, the inlet valve is partially opened to generate the oil spray to impregnate the test object. The test object remains 30 minutes in the bottom chamber before draining the insulating fluid.

In the case of the RFT insulation prototype, the Kraft paper was firstly impregnated with MO following the process explained before. Then, the impregnation plant was cleaned removing the MO from all its parts. Then the surface of the solid insulation was flushed with NE to wash the remains of MO on the surface of the paper (Fig. 2b), as is carried out during transformer retrofilling processes. Finally the tank of the impregnation plant was filled with NE under vacuum, aiming at emulating the process outlined in [11], which recommends to refill the transformer tank with NE under vacuum. Finally, the insulation prototype is introduced into a vessel filled with NE and placed in an oven for testing.

As explained before, the process was repeated to prepare the prototypes of transformer insulation filled with MO (MOFT) and with NE (NEFT).

### C. *Testing procedure*

In order to emulate the operation of the transformer and to evaluate the possible migration of MO towards the NE in the case of the retrofilled insulation, the three prototypes were placed in a vacuum oven where they remained at temperature 60$^o$C and 1 mbar for four months. The vacuum was applied to prevent oxidation of the liquids although it is unlikely that significant oxidation takes place at the 60$^o$C.

Oil samples were taken periodically during the test to determine, by a chemical method explained in the following section, the progressive contamination of NE with MO migrating from the paper throughout the test.

Additionally, dielectric response measurements in the frequency domain (FDS) were carried out on the three insulation prototypes periodically. Since the dielectric response is temperature dependent, the oven temperature was reduced for some hours before each evaluation of the test objects, so all the measurements were carried out at 20$^o$C [12].

Oil sampling and FDS measurements were carried out 0, 10, 35, 60, 82, 94 and 117 days after the test objects were put in the vacuum oven.

After four months of testing, the prototypes were extracted from their vessels and the dielectric response of the eight layers of Kraft paper that constituted them were characterized to study the distribution of MO throughout the thickness of the RFT insulation prototype.

## III. EVALUATION OF THE RATE OF CONTAMINATION BY CHEMICAL METHODS

Samples of fluid were periodically taken from the RFT prototype to evaluate the change on the contamination rate of the NE with MO during the experiment by means of chemical methods.

Several authors have proposed the use of physicochemical markers such as kinematic viscosity, flash point or fire point to determine the rate of contamination of a NE with MO [3], [13]. The authors of this work have developed and tested a chemical method based on the determination of the iodine value (IV) of a fluid sample to determine its content in MO and NE. This was the method used in this work to evaluate the contamination rate of MO in NE throughout the experiment. The proposed methodology is fully described in a previous paper [14] but some basic aspects of the method are outlined below.

### A. *Iodine value determination*

Iodine value (IV) indicates how unsaturated an oil is, expressing the mass of iodine that reacts with 100 grams of substance. MOs are saturated liquids composed mainly of naphthenic and paraffinic chains that usually have no double bonds, while those bonds are part of the molecular chain of NEs. The IV of both types of fluids are likely to differ greatly, although the IV of a MO is be affected by the presence of unsaturated (olefin or aromatic) impurities in it. According to the information provided by the supplier of the commercial MO used in the study, the presence of aromatics or olefins in its composition is less than 4% [15].

The authors measured the IV of the two dielectric fluids (NE and MO) used in this work, obtaining 0.8 g$I_2$/100g for MO and 128 g$I_2$/100g for NE, summing up that IV determination could be a suitable method for this characterization. Then, mixtures of fresh MO and NE containing 0%, 5%, 10%, 25%, 50% and 100% of MO by volume were prepared. The IV of the mixtures is shown in Fig. 3.

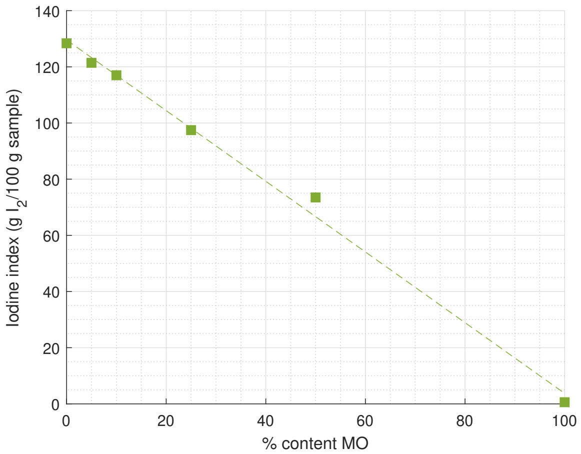


Fig. 3. Iodine value of mixtures of MO and NE.

As can be seen, the relationship between the IV of the mixtures and their percentage of MO by volume fits with a linear trend line (R$^2$=0.994). As IV for MO is approximately zero, the trend line can be expressed as eq. 2.

$$IV_{mix} = IV_{NE} \cdot (1 - \frac{\%MO}{100}) \tag{2}$$

where IV$_{NE}$ is the IV of the NE used in the mixture, %MO is the percentage by volume of MO present in the mixture and $IV_{mix}$ is the IV of the mixture.

Since the IV of the used NE is known, the determination of IV in a sample taken from a retrofilled transformer can be used to calculate the rate of contamination of the NE with MO according to eq. 3.

$$\%MO = (1 - \frac{IV_{mix}}{IV_{NE}}) \cdot 100 \tag{3}$$

## B. Evaluation of the contamination after retrofilling

Samples of liquid insulation were taken periodically from the vessel of the RFT prototype after the retrofilling. The mass of fluid required for IV evaluation is small, around 0.15 g. The IV of the samples was determined and then eq. 3 was applied to estimate the contamination rate of the NE with MO.

The results of both the IV values and the contamination ratios calculated using eq. 3 are shown in Fig. 4.

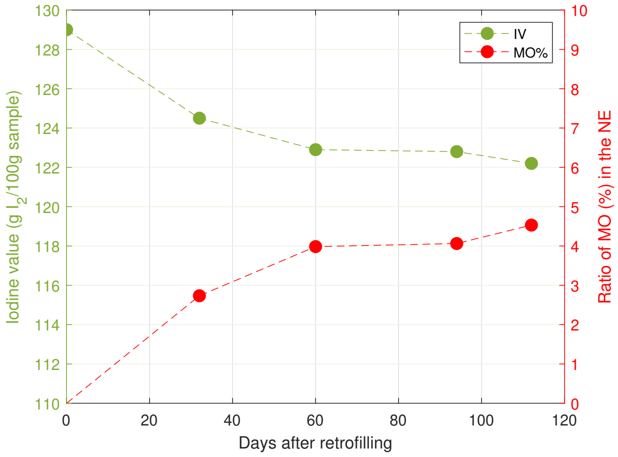


Fig. 4. Evolution of the IV and the contamination rate during the days after retrofilling

As can be seen in Fig. 4, the IV of the fluid in the RTF prototype just after retrofilling (i.e. time 0) is similar to that of the NE. Subsequently, the IV decreases significantly during the test until day 60; after that, the drop of IV becomes slower. This result reflects that the migration of MO is relatively fast in the first weeks after the retrofilling but migration tends to stabilize after the second month. In the last part of the test the amount of MO that flows out the cellulose seems to be minimal.

According to Fig. 4, the contamination rate of the NE with MO by the end of the test reaches almost a 5%. This contamination rate is in agreement with the estimations of other authors [2], [13]. Nevertheless the percentage of MO in the NE could have reached higher values if the proportions of paper and fluid or the prototype testing conditions (i.e. oil flow, temperature profiles) had been different.

The chemical evaluation suggests that the flow of MO from the paper towards the oil is limited. As will be explained in further sections, the dielectric evaluation of the paper layers evinces that most of the MO remains adsorbed in the cellulose by the end of the test.

# IV. EVALUATION OF THE RETROFILLING PROCESS BY DIELECTRIC RESPONSE MEASUREMENTS

To deepen into the evaluation of the retrofilling process and to test other methods that could be of application to get insight into the migration of MO towards the paper in retrofilled transformers, the dielectric response of the three insulation prototypes (MOFT, NEFT, RFT) was characterized at different times of the experiment.

The dielectric response of a material depends on the properties of the material and also on its condition. The characterization of the dielectric response has been mainly used as a diagnostic method for transformer oil-paper insulation to get information on its water content and aging condition, but Breazeal et al. used this method to evaluate the migration of MO towards the ester in several retrofilled transformers of small size [9].

## A. Dielectric response measurements

Dielectric response in the frequency domain was applied to characterize the three insulation prototypes. The measurements were carried out with the tester DIRANA (Omicron). The complex capacitance ($\hat{C}(\omega)$) of the three objects was measured in a frequency range between 500 $\mu$Hz and 1000 Hz. The complex capacitance is defined as:

$$\hat{C}(\omega) = C'(\omega) + iC''(\omega) = C_0 \cdot \hat{\varepsilon}(\omega) \tag{4}$$

where $C_0$ is the geometric capacitance of the test object and $\hat{\varepsilon}$ is the complex permittivity with real and imaginary components $\varepsilon'$ and $\varepsilon''$. The real part of the complex capacitance, C', is the capacitance of the test object, while the imaginary part, C", is proportional to the dielectric losses of the material.

Additionally, tan delta of the samples was derived from the measurements:

$$\tan\delta(\omega) = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} \tag{5}$$

The measuring circuit applied for the tests is shown in Fig. 5. Voltage was supplied to the insulation prototypes though a screw electrode that made contact with the metal mesh, while the inner electrode was grounded. Since the material placed between the electrodes is the solid insulation, the complex capacitance characterized in the FDS tests was that of this material. In a previous work, the same measuring principle was tested, proving that the influence of the external media on the measurements is almost negligible [10].

## B. Results

As explained before, the complex capacitance of the three prototypes was measured after the impregnation process and then measurements were repeated periodically to evaluate the possible migration of MO towards the NE in the RFT prototype.

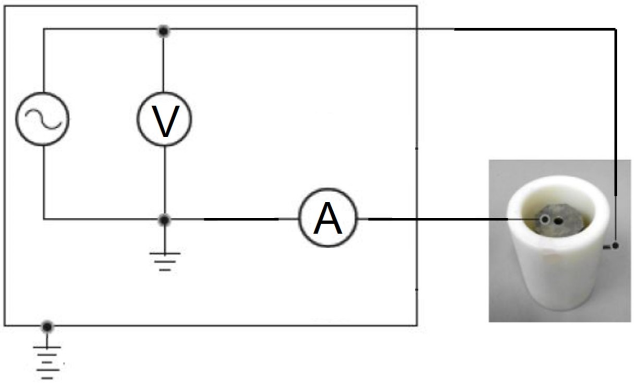


Fig. 5. Measuring scheme

The initial FDS measurements on the three insulation prototypes are shown in Fig. 6. These measurements were taken before subjecting the prototypes to heating. When comparing the initial complex capacitance of the three prototypes, it is observed that the dielectric losses (C”) of the MOFT and the RFT are almost identical at high and medium frequencies. At lower frequencies the dielectric losses of the RFT are higher than those of the MO, probably due to the effect of the interfacial polarization that appears because of the presence of two insulating liquids [16].

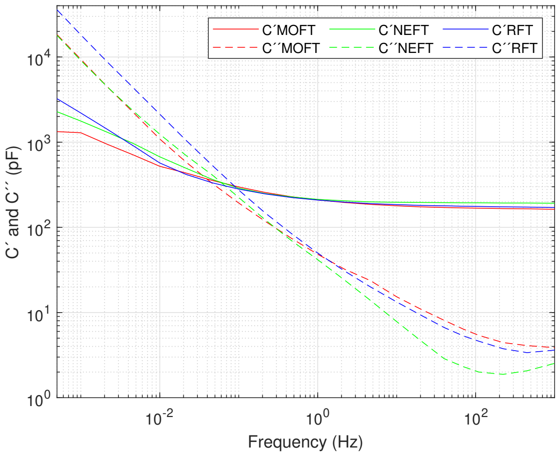


Fig. 6. Initial measurements on the three insulation prototypes

The initial relative permittivity of the three prototypes of solid insulation, and its variation in time is shown in Fig. 7. The permittivity values were calculated from C’ at 50 Hz applying eq. 1. As it can be seen, the permittivity of the RFT prototype at the beginning of the test was very close to that of the MOFT prototype. This is in agreement with the chemical evaluation and seems coherent with the fact that the paper on the RFT prototype was initially impregnated with MO and only a small amount of NE is expected to be adsorbed in the paper during the retrofilling process because of the flushing of the surface with NE (Fig. 2b).

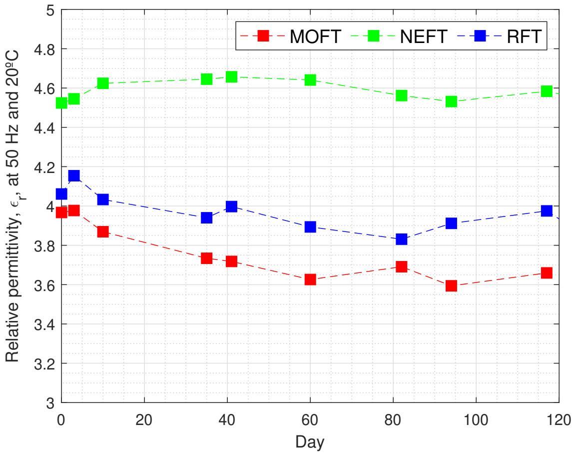


Fig. 7. Relative permittivity at 50 Hz and 20$^o$C during the testing time

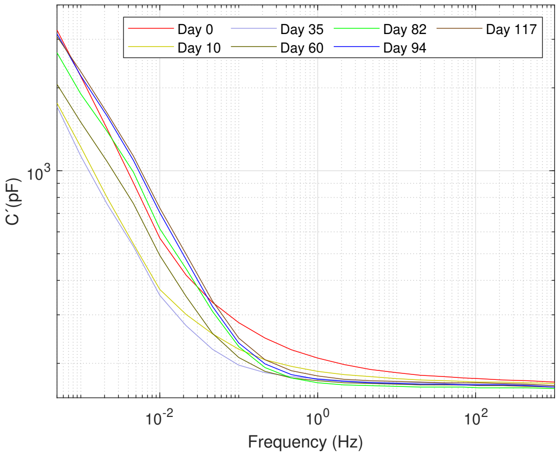
In subsequent measurements, the value of $\varepsilon_r$ for RFT always remained between the permittivity values of MOFT and NEFT prototypes. Nevertheless, the permittivity values of the three prototypes experienced some change throughout the testing period, what makes it difficult to extract conclusions about the migration of MO towards the NE in the RFT insulation prototype. As will be discussed later, the observed changes may be related, in part, to the moisture dynamics in the prototypes. The greatest change was observed in the MOFT, whose permittivity values decreased by 7.7%. The permittivity in the NEFT prototype remained quite stable and in the RFT prototype it showed two trends: an initial decrease similar to that observed on the MOFT prototype, followed by a certain increase. The average values of $\varepsilon_r$ throughout the test were 3.85 for MOFT, 4.00 for RFT and 4.62 for NEFT.

Fig. 8 shows the real and imaginary part of the complex capacitance of the RFT insulation prototypes at different times of the experiment. It can be observed that the dielectric losses (Fig. 8b) do not show a monotonous trend: they first decrease and then increase. To understand the reason for this behaviour, the curves obtained in the MOFT and NEFT must be analysed.

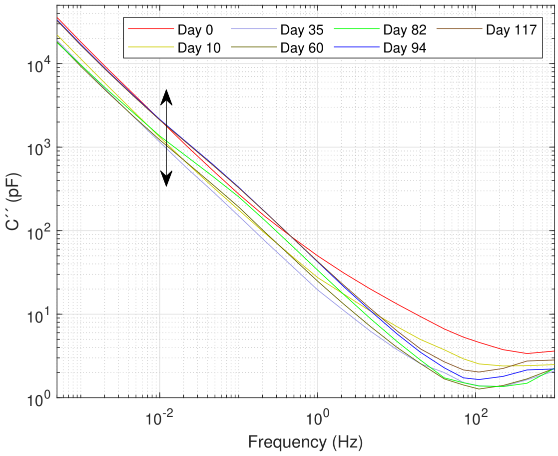
Figs. 9 and 10 show the real and imaginary part of the complex capacitance of the MOFT and NEFT insulation prototypes at different times of the test.

It can be observed that the dielectric losses (C”) in the MOFT prototype tend to decrease as the testing time increases (Fig. 9b), while the behaviour of NEFT is the opposite and the dielectric losses increase (Fig. 10b). These different trends may be attributed to moisture migration between solid and liquid insulation of the two insulation prototypes. Before starting the test, the water content in the MO was 7 ppm and that of the NE was 146 ppm. Although the Kraft paper was subjected to drying before impregnation, a certain amount of water remained adsorbed in the paper. When paper is immersed in liquid insulation a migration of moisture between both media is established until equilibrium is reached, that is, when relative moisture between both media is the same.

In the MOFT prototype, it is likely that when temperature rises to 60$^o$C part of the water contained in the paper migrated towards the MO, since water solubility in oil increases with temperature. It should be noted that the test vessel was opened during the test and vacuum was applied in the oven, so it is

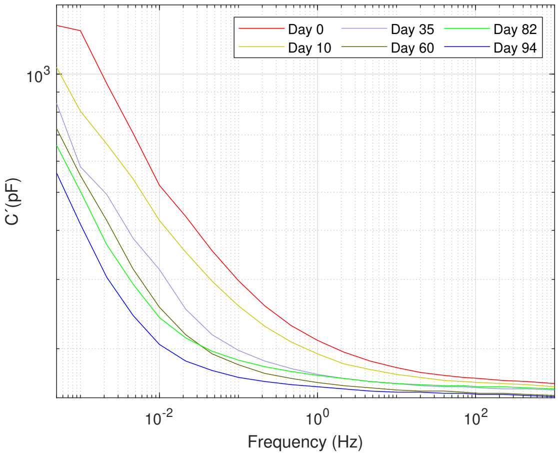


(a) C’ RFT

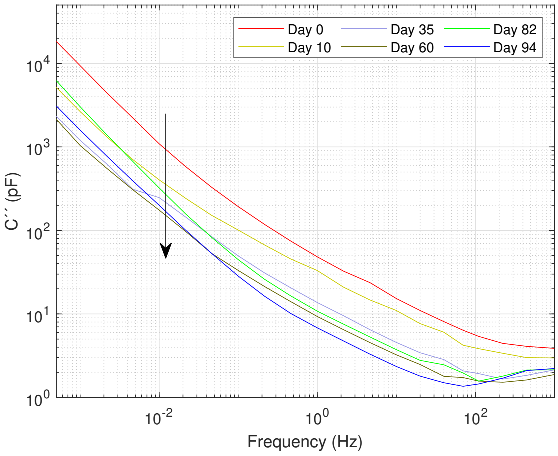


(b) C” RFT

Fig. 8. Real and imaginary components of the complex capacitance on RFT insulation prototype over time



(a) C’ MOFT



(b) C” MOFT

Fig. 9. Real and imaginary components of the complex capacitance on the MOFT insulation prototype over time

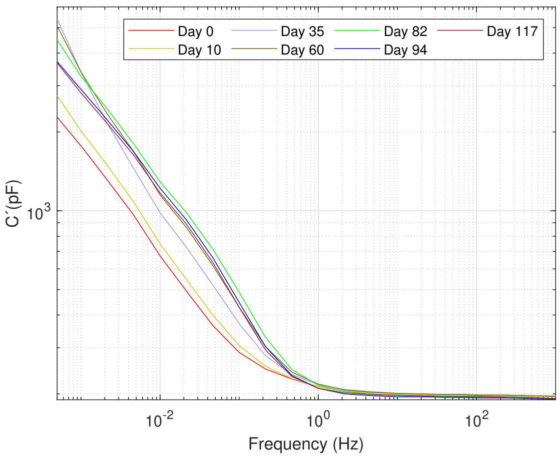
likely that water in the MO progressively migrated to the air in the vacuum oven drying the insulation prototype over time. This could be an explanation for the reduction in the dielectric losses observed in this prototype. Since the test was carried out at $60^{o}$C, significant aging is not expected.

The opposite may have happened in the NEFT prototype. Due to the relatively high water content in the NE at the beginning of the test, some water may have migrated into the paper increasing its moisture content and, consequently, its dielectric losses. As all three prototypes were in the same oven, some of the water evaporated from the MOFT prototype could have contaminated the NEFT prototype, as the ester is hydroscopic and may have adsorbed some moisture from the air in the oven.

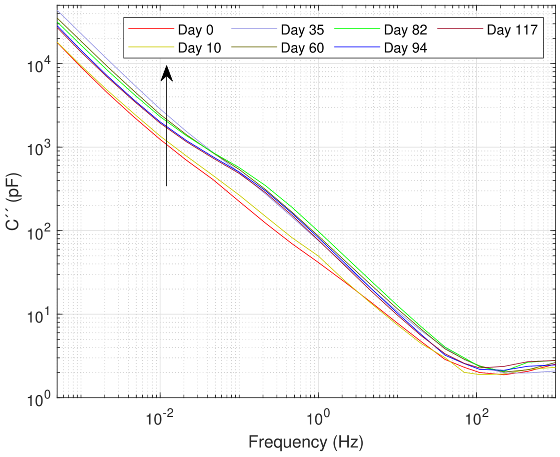
To confirm this hypothesis, the dielectric response of the prototype was compared with measurements of a previous work [10] that had been taken from test objects with similar geometry preconditioned with different moisture contents. The physical magnitude used for the analysis was tan delta, due to its independence from the geometry of the test object in the frequency range analized [16]. Fig. 11 shows the comparison between the measured tan delta of the MOFT prototype (solid lines) and the measured tan delta of the objects with known moisture content (dotted lines). It can be seen that tan delta decreases as the relative moisture content of Kraft paper decreases, what is consistent with the moisture migration hypothesis above. Furthermore, Fig. 11 suggests that the solid insulation of the MOFT prototype had a moisture content of around 4% at the beginning of the test, which dropped to 1% at the end of it.

The complex capacitance of the NEFT prototype did not vary as much as that of the MOFT throughout the test. There was, certainly, a small change that showed an opposite behaviour to that of the MOFT. As the experiment progressed a certain increase in losses was observed. It is likely that the ester adsorbed some of the water that migrated from the MOFT prototype since that material has a certain affinity for water.

In the case of the RFT (Fig. 8b), the observed variations could be related to two exchange mechanisms: one of them is the migration of MO from the Kraft paper to the surrounding NE and the re-impregnation by NE and the other one is the moisture exchange between the cellulose and the surrounding



(a) C' NEFT



(b) C" NEFT

Fig. 10. Real and imaginary components of the complex capacitance on NEFT insulation prototype over time

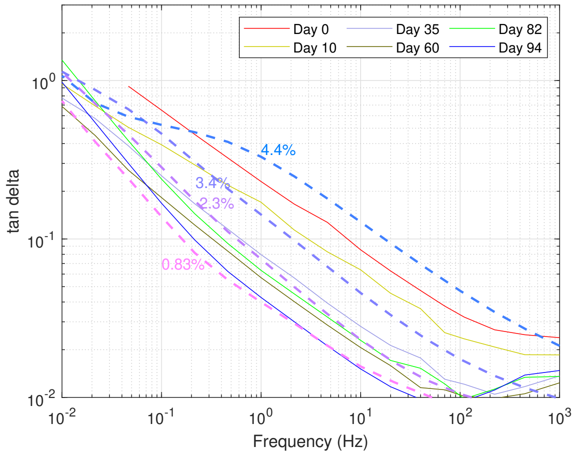


Fig. 11. Comparison of the tan delta of the MOFT prototype at different time instants (solid lines) and that of several test objects with known moisture content (dotted lines)

fluid. The evolution of the dielectric losses suggests that the migration of MO towards the NE is probably the prevailing phenomenon during the first three months of the test: the dielectric losses of the RFT decrease as occurs in the case of MOFT. In subsequent measurements, the trend appears to reverse, increasing losses as the NEFT prototype does. This suggests that the Kraft paper is mostly impregnated with MO at the beginning of the test, but as test time progresses some of the MO comes out of the cellulose and NE takes its place, so that the C" trend of the RFT prototype resembles that of the NE-impregnated prototype.

The results of the dielectric measurements suggest that several factors related to water moisture dynamics influenced the results of the dielectric response tests. Although a different design of the experiment could have prevented some aspects, as the moisture migration between prototypes, moisture dynamics between oil and paper insulation is always present in real transformers and on insulation prototypes and this factor will always have an impact on dielectric response tests.

The main conclusion that can be extracted from the dielectric response measurements is that several factors have influence on the results of these tests. This complicates the application of the method to evaluate MO migration from solid to liquid insulation in retrofilled transformers.

## V. OIL DISTRIBUTION IN THE KRAFT PAPER

To complete the study, additional dielectric response tests were carried out aimed at determining what type of oil remained adsorbed in the different layers of paper of the RFT insulation prototype after four months of testing. The chemical evaluation suggests that the migration of MO towards the oil in the RFT prototype was not big and was probably limited to the most external part of the paper. On the other hand, the dielectric response tests were not conclusive and indicated that several processes took place during the test which influenced the measurements.

Once the experiment was over (117 days after the three prototypes were placed in the oven) the insulation prototypes were taken out from the vessel and their metallic mesh was removed. Each of the eight layers of Kraft paper that constituted the solid insulation of the prototypes was separated from the rest and its 50 Hz capacitance was measured using the FDS tester DIRANA and a Keithley 8009 test cell.

The capacitance measurements on the different layers of the three prototypes are shown in Fig. 12. Each point in the graph represents the capacitance of a single layer of paper from the prototypes.

The capacitance of the individual layers of the MOFT and NEFT prototypes were pretty constant with mean values 71.1 pF and 79.9 pF, respectively. The light red and green areas represent the 95% confidence interval for those capacitances.

Regarding the capacitance of the RFT paper layers, it may be observed that the measured values are close to the NEFT capacitance (or within its confidence interval) for the first three layers, while for the outermost ones the capacitance is within the MOFT confidence interval. This suggests that, four months after retrofilling, some migration of MO from the RFT solid insulation has taken place, but it has only affected the most

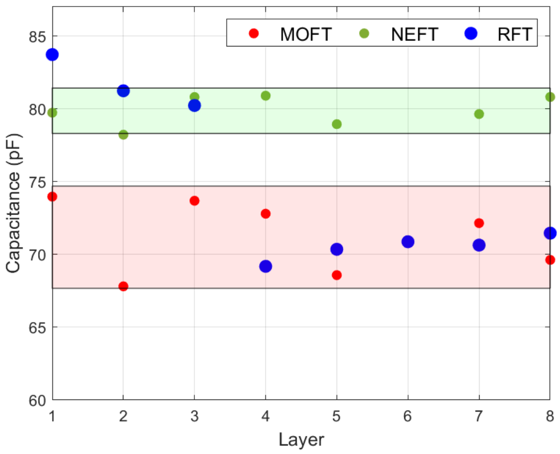


Fig. 12. Capacitance of each single layer of the solid-insulation prototypes

external part of the insulation. By the end of the test, the outer layers of paper seem to be impregnated with NE, while the inner layers remain impregnated with MO.

It should be noted that the only process that has driven the oil migration in this experiment was the rise in temperature. In a transformer there are other factors that may speed up this process, such as the forced oil flow inside the tank. More research will be needed to study the influence of those factors.

## VI. CONCLUSION

This work analyses the migration of MO from the solid insulation towards the ester after retrofilling a transformer. The study was carried out on a laboratory prototype that emulates the oil-paper insulation of a retrofilled unit. The prototype was subjected to temperature, and the migration of MO was studied during four months. Two additional prototypes that emulated the insulation of a MO-filled transformer and a NE-filled transformer respectively were tested in parallel and taken as a reference.

A new method developed by the authors was used to quantify the contamination rate of the NE surrounding solid insulation with MO in a retrofilled transformer. The method was based on the evaluation of the iodine value of the liquid mixtures; this marker gives an indication about on the presence of saturated or insaturated bonds in the molecules and it leads to a reliable estimation of the volume of MO dissolved in a NE. The chemical evaluation suggested that the migration of MO from the solid insulation mainly takes place once the transformer is subjected to heating after the retrofilling, but the migration stabilizes some weeks later time. The contamination rate by the end of the test was below 5%.

The dielectric response of the Kraft paper was also used to get information on the migration of MO from solid insulation towards the ester in retrofilled transformers. Extracting information from these tests was not easy since MO migration coexist with moisture dynamics between oil and paper insulation, which impacts on the results making the interpretation of the measurements complicated. Moisture dynamics is always present in transformers, so the interpretation difficulties would also appear if dielectric response methods were used to quantify the contamination rate in real retrofilled units.

The gradient of MO throughout the Kraft paper thickness was also studied using capacitance measurements of the different layers that constituted the solid insulation of the RFT prototype, obtaining that MO migration occurs mainly in the outermost part of the solid insulation, remaining around two thirds of the initial MO in the innermost part of it.

Research in this study still continues to take into account other phenomena that also take place inside the transformer such as thermal phenomena and oil flow due to forced cooling.

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