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Moisture dynamics in natural-ester filled transformers

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Abstract

Due to the global trend in the industry to work towards sustainability and clean energy, utilities and transformer manufacturers focus on the design of environmentally friendly devices. In this context, the use of natural esters as transformer's liquid insulation is becoming an habitual practice in distribution transformers. These fluids make possible the operation of transformers with lower fire risk, what is important for certain applications. Additionally natural esters are biodegradable and their application minimizes the risk of soil contamination in case of fluid's leak. One of the differential characteristics of ester fluids is that they have higher affinity for moisture than mineral oils, absorbing masses of water up to ten times greater than conventional insulating fluids under similar working conditions. This fact changes the water distribution between the solid and liquid insulation that is typically found in mineral-oil filled transformers. Moisture content in insulating materials remains as one of the most important parameters determining the life cycle of transformers, hence the importance of fully understanding its behaviour. Although many actions are being taken to spread the use of ester fluids, not many works about the performance of water in ester-cellulose systems haven been published to date.

In this work, an analysis on the moisture dynamics in transformers insulated with natural esters is presented. In the first part of the paper the main parameters that influence the moisture distribution between oil and paper are obtained either for the case of an ester or a mineral oil being used as insulating fluids. Then, simulations are carried out in which different temperature profiles are assumed and the evolution of the moisture distribution between the solid and liquid insulation is analysed. Finally some conclusions of relevance for the management of transformers insulated with natural esters are provided.

Key words: Transformer, Oil-cellulose insulation, Natural ester, Moisture dynamics, Dynamic loading, Asset management

1 Introduction

In the last years the interest in the application of natural and synthetic esters to electric equipments as a substitute for mineral oil has grown significantly [1]. Currently, these fluids are mainly being used in small and medium sized distribution transformers [2] although some experiences in power transformers have been reported as well [3]. The implementation of these fluids is expected to increase following the European regulation on Ecodesign Transformers, which second stage is planned by July 2021. Such regulation defines specific rules to be observed in the design of ecodesing power and distribution transformers, which includes the application of new materials. Ester fluids are biodegradable liquids and present some other advantageous properties, as their high fire point, what makes them a valuable alternative to mineral oils. On the other hand, they present some limmitations like their cost and their relatively higher viscosities and oxidation rates [4].

One of the differential properties of natural esters is that they are able to absorb much greater amounts of water than mineral oils [5]. This fact has an impact on the moisture distribution in the oil-paper insulation and the moisture dynamics processes inside the transformer.

Moisture is one of the variables that deserves more attention in transformer's life management. An excessive water level in the insulation increases the presence of partial discharges, reduces the dielectric strength of the insulation, accelerates the paper ageing rates and increases the risk of failure of the equipment [4]. According to IEEE standard C57.91-2011 [6], a transformer with moisture content in its insulation greater than 4% is too wet to be operated safely. During the transformer life, the water content of its insulation always increases, because of the degradation of the cellulose molecular chain by thermal stresses and oxidative processes [7], and also because of water ingress by the conservator or through leaks in the tank. Thus, it is common to find moisture levels in the solid insulation between 3 - 4% in weight in older transformers and it is not unusual to find high humidity levels in newer transformers as well, for example, in units that have been subjected to on-site repairs.

Because of the hydrophobic nature of oil and the hydrophilic character of cellulose, water in a transformer is mainly absorbed in the solid insulation [7]. However, as temperature increases the water solubility of oil increases while the water adsorption capacity of cellulose decreases and part of the water in the solid insulation migrates from cellulose to oil. At decreasing temperatures the cellulose materials again take up water molecules from the oil [7]. The temperature distribution of a transformer is related to its load and the atmospheric temperature and thus, as these variables are subjected to continuous changes, the oil-cellulose insulation of transformers will generally work under transient moisture conditions.

Being able to predict the behaviour of moisture in the transformer insulation is important to optimize the transformer operation, the maintenance programs, and to estimate the remaining life of the transformer. Different hazardous situations can arise during the operation of transformers with high moisture contents, such as the formation of free water in transformer oil during a cooling cycle, or the accumulation of high water concentrations, or the formation of bubbles at the interface oil-paper. Those types of events can compromise the dielectric strength of the oil-paper insulation and the integrity of the equipments. Experimental evidence on the effect of the moisture migration processes on the formation of partial discharges and breakdown of the insulation has been provided by several authors [8–11]. In [10] Sokolov proposed a rule-based approach to evaluate if a temperature variation can be safely applied to a transformer taking into account its moisture level. In [8], Sikorski et al. monitored the partial discharge activity in field transformers observing an increase of this activity during cooling and heating cycles, and attributing this increase to the moisture migration processes.

Additionally, the behaviour of moisture inside the transformer insulation is a key aspect in dynamic loading studies. Dynamic rating programs are based in the calculation of the temperature profiles of the transformer for certain loading profiles and the estimation of the loss of life of the insulation for these temperatures [12,13]. If the solid insulation operates with high humidity levels the ageing rate of the paper is higher [14,15] and thus a lower hot-spot temperature would be acceptable to preserve the condition of the solid insulation.

To date not many works have been published on the behaviour of moisture in cellulose-ester systems. A few authors have recently reported works regarding the determination of the equilibrium curves in ester-cellulose systems. In this line, Jovalekic obtained moisture equilibrium curves using natural esters as insulating liquids and high density (HD) pressboard and Nomex as cellulosic material [16], Vasovic developed moisture equilibrium curves using natural esters and a combination of Kraft paper and pressboard as cellulosic insulation [17] and Przybylek [18] determined moisture equilibrium curves in insulating systems combining cellulose materials with different ageing levels impregnated with different insulating liquids. Additionally, Zhang [19] and Villarroel [20] proposed expressions for the moisture diffusion coefficient of Kraft paper impregnated with a natural ester considering the dependence of the coefficient with temperature and moisture concentration.

The main objective of this work is to study the dynamic behaviour of moisture in transformers insulated with natural esters, and to compare this behaviour with that of transformers insulated with mineral oil. Moisture equilibrium curves and diffusion coefficients have been experimentally obtained for cellulose-oil systems considering either natural esters as mineral oil as insulating fluids. The moisture dynamics was simulated by means of a theoretical model for both types of liquid insulation, getting a dynamic map on the moisture distribution in the solid insulation under different transformer operating conditions.

2 Distribution of moisture between solid and liquid insulation of transformers

The insulating fluid and the cellulose insulation that coexist inside the transformer tank have a very different behaviour in relation to water. While cellulose materials are hydrophilic, oil is highly hydrophobic. In consequence, most of the water in a transformer remains stored in the solid insulation and just a small proportion of it is dissolved in oil.

To determine how moisture is distributed between paper and oil for certain conditions it must be considered that if there is a thermodynamic equilibrium between a piece of cellulose insulation and its surrounding media, an equilibrium between the partial pressures of water in both media and then between their relative humidities is also established. In this way, the relative saturation in the cellulose and the oil must verify equation 1.

$$W_{rel,cel} = W_{rel,oil} \tag{1}$$

where $W_{rel,cel}$ is the relative moisture content of the cellulose, $W_{rel,oil}$ is the relative moisture content of the oil.

Several authors have developed equilibrium curves [17,18,**?**,23] that makes possible to obtain the moisture content of cellulose insulation and of the oil for different temperatures under equilibrium conditions. The distribution of moisture between oil and paper is not static but varies with the temperature. When temperature rises the water saturation limit of oil increases while the water adsorption capacity of cellulose decreases. Any change on the transformer temperature map is accompanied by a disequilibrium on the moisture distribution. If the temperature rises, part of the water migrates from cellulose insulation to oil. Conversely, if temperature decreases, the migration of moisture takes place in the opposite direction. Fig. 1 illustrates the phenomena.

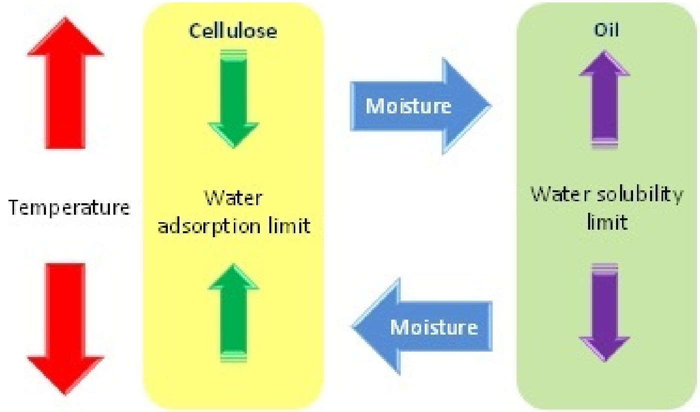


Fig. 1. Moisture migration within oil-paper insulation.

The operation of a transformer involves a continuous thermal disequilibrium because of the load and ambient temperature fluctuations the transformer is generally subjected to. Those changes of temperature will trigger moisture migration processes in which water will flow from cellulose to oil if temperature rises and from oil to cellulose if temperature drops. Although the time constants for the moisture migration processes depend on several factors (as the properties of the materials, the moisture concentration and the temperature [21]) they are always larger than the thermal time constants of the transformer, what implies that the moisture equilibrium will hardly ever be attained in a transformer under operation [22]. For this reason the estimation of the moisture dynamics transformer will require the use of dynamic modelling.

As the polarity of natural ester fluids is higher than that of mineral oils, these fluids will admit higher amounts of water in solution before reaching the saturation level. This implies that in a cellulose-ester system the moisture equilibrium point be more displaced towards the fluid than in the case of a mineral-oil-ester system. This fact will introduce changes in the moisture dynamic processes in these transformers. The moisture equilibrium curves of two natural esters and a mineral oil have been experimentally obtained in this work. These curves will be used to model the moisture dynamics of the ester-filled transformer.

2.1 Moisture equilibrium curves for natural esters and mineral oil.

The equilibrium curves that provide the distribution of moisture between cellulose and oil as a function of temperature have been experimentally determined in this work considering a mineral oil (Nytro Taurus, from Nynas) and a natural ester (Biotemp from ABB)as insulating fluids. To this end, the method proposed by Oommen in [23] was used, which is based in the fact that the relative moisture content W_{rel} in adjacent materials become identical under equilibrium conditions, and thus the cellulose-oil equilibrium curves could be obtained by combining the moisture-in-oil versus relative-humidity curves in air with moisture-in-paper versus relative-humidity curves in air. In this work, the paper-air equilibrium condition were obtained from the curves provided by Jeffries in [24] (Fig. 2), and the solubility curves of the natural ester and the mineral oil were experimentally obtained.

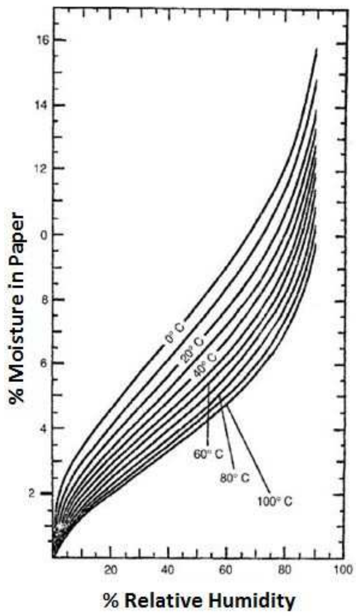


Fig. 2. Moisture in paper as a function of relative humidity of the ambient by Jeffries. Taken from [24].

The water solubility of oil can be expressed in Arrhenius forms as expressed in equation 2

$$LogW_S = A - \frac{B}{T} \tag{2}$$

where W_s is the saturation solubility of water in oil in ppm and T is the temperature in Kelvin, and A and B are the parameters dependent on the properties of the fluid.

In order to determine the parameters A and B for the fluids studied in this work, experiments were carried out in which samples of the two fluids were placed inside an environmental chamber under controlled conditions of humidity and temperature. The moisture content of the the oil samples was measured every two days until the equilibrium was reached. A sample was considered to be in equilibrium, once its moisture content remained constant for 6 days.

All the moisture measurements were performed using Karl Fischer titration method, according to the international standard IEC 60814 [25].

The absolute moisture content of the two fluids was determined for relative humidity (RH) 50% and temperatures 30, 40, 50 60, 70 and 80 $°C$. Table 1 shows the moisture contents measured on the two analysed oils after the equilibrium was reached for all the tested conditions. As it can be seen, the natural ester attained much higher moisture contents at the end of the conditioning period than the mineral oil for all tested temperatures.

Table 1
Moisture content of the two insulating fluids at RH 50% and variable temperature.

	Moisture content (ppm)					
	30 $°C$	40 $°C$	50 $°C$	60 $°C$	70 $°C$	80 $°C$
Mineral oil	38	58	80	119	171	228
Natural ester	575	699	837	1001	1182	1330

The water saturation limits of the analysed fluids were obtained, using the experimental data measured at RH 50% and equation 3.

$$W = W_s \cdot RH \tag{3}$$

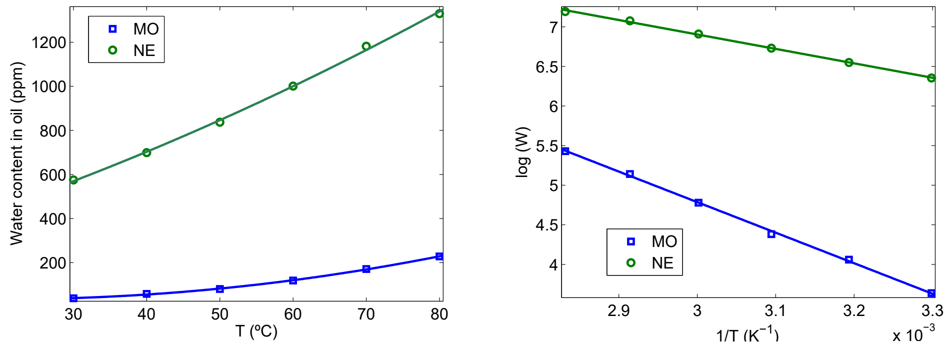
where W is the moisture content of the oil (ppm), W_s is the water saturation solubility of the oil (ppm) at temperature T, and RH is the relative humidity of oil, which is equal to the relative humidity of the surrounding air (%).

Fig. 3 shows the maximum amounts of water accepted by each oil without being saturated as a function of temperature. As it can be seen the saturation limit for mineral oil is considerably lower than that of natural ester. The parameters of the solubility equation (2) were calculated for the two fluids, finding the values provided in table 2.

Table 2
Parameters A and B of equation 2 calculated natural ester and mineral oil.

	A	**B**
Natural ester	5.67	791
Mineral oil	7.44	1,686

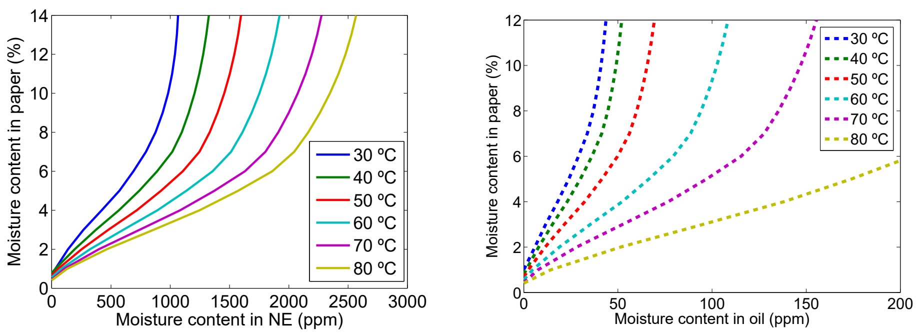
Finally, the oil-cellulose moisture equilibrium curves for the analysed fluids are obtained by combining the obtained moisture solubility limits and the curves displayed in Fig. 2. These curves were found by Jeffries [24] and represent the moisture content reached by cellulose (% in weight) when it is exposed to air with different relative humidities under different temperatures.



(a) Water solubility. (b) Parameter fitting.

Fig. 3. Water solubility of natural ester and mineral oil as a function of temperature and the linearised values using Arrhenius equation.

Fig. 4 shows the equilibrium curves obtained for a cellulose-natural ester insulation system (a) and for a paper-mineral oil system (b). As it can be seen both ester fluids are able to absorb a much greater amount of water under the same conditions of temperature and moisture in paper what, as will be shown in this work will have a significant impact on the moisture dynamic processes of those systems.



(a) Natural ester (b) Mineral oil.

Fig. 4. Moisture equilibrium curves for paper-oil system in natural esters and mineral oil.

It must be highlighted that the curves shown in Fig. 4 are only valid for moisture equilibrium conditions. Although it is unlikely that equilibrium is reached in a transformer in service, these curves are important because they will set the boundary condition for solving the differential equations that describe the moisture dynamics within the transformer insulation as will be explained next.

3 Simulation of the moisture dynamics in the oil-cellulose system

Under normal conditions, the temperature of a transformer is subjected to continuous variations during its operation because of fluctuations on the load and changes on ambient temperature. These temperature changes provoke the migration of moisture from paper to oil, when temperature rises, and from oil to paper as temperature drops. These migration processes are not instantaneous and involve two stages: The diffusion of moisture throughout the solid insulation, and the release or adsorption of water at paper-oil interface. The typical time constants of these two processes are significantly different and while the migration of moisture inside the solid is a very slow process, the exchange at the interface can be considered instantaneous. The time constants are also dependent on the type of insulating fluid that is used in the transformer.

In a previous work, the authors of this paper developed a theoretical model that can be used to simulate the moisture dynamic processes that take place in the transformer insulation [26]. In order to simmulate moisture migration proceses, the initial distribution of moisture within the solid insulation and the temperature profile during the considered period should be provided to the model as input data. The temperature profile can be calculated by means of the models provided in the Std C57-91-2011 [6] given a certain loading profile.

The model assumes a one dimensional geometry and calculates the distribution of moisture at a particular height of the insulation. The moisture distribution at different points of the transformer could be obtained by running several simulations in parallel, considering the temperatures calculated for different heights of the winding and specifying adequate insulation thickness.

The migration of moisture inside cellulose is modelled as a diffusion phenomenon by means of Fick's second law:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D \cdot \frac{\partial c}{\partial x}\right) \tag{4}$$

where c is the local total moisture concentration in cellulose, t is the time, x is the distance into the material in the direction of the moisture migration.

D is the moisture diffusion coefficient of the solid insulation, which is the the parameter that characterizes how fast water migrates through the insulation before reaching the surface where the exchange of water between oil and paper takes place. The diffussion cofficient of cellulose insulation depends on the insulation properties (i.e. density, thickness, aging condition),but also on its opperating conditions and on the fluid that impregnates it. Several authors have proposed expressions for the diffusion coefficient of oil-paper insulating systems which can be applied to model the moisture migration processess in cellulosic materials [27].

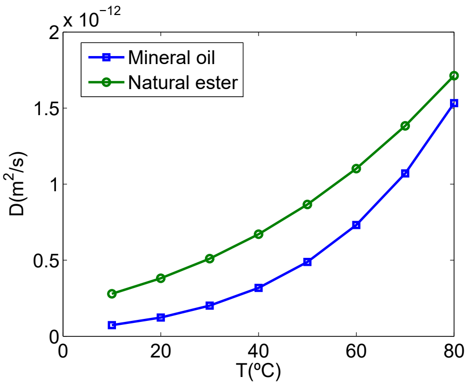
The authors of this work have carried out extensive experimental work to determine the diffusion coefficients of cellulose insulation impregnated with different types of fluids. The following expressions were found for the case of cellulose insulation impregnated with the mineral oil Nytro Taurus (equation 5) and with the natural ester Biotemp (equation 6).

$$D_{MO} = 2.510^{-9} \cdot l^{4.3} \cdot e^{\left(0.2 \cdot c - \frac{3,164 \cdot l^{0.29}}{T}\right)} \tag{5}$$

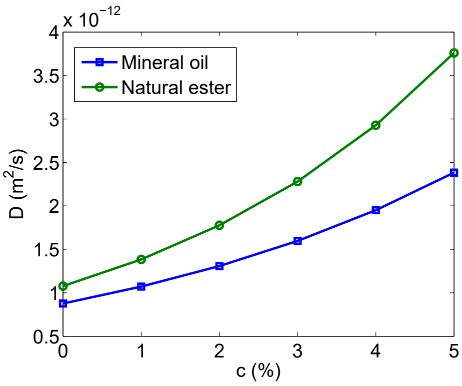
$$D_{NE} = 1.2 \cdot 10^{-7} \cdot l^{-3.7} \cdot e^{\left(0.25 \cdot c - \frac{4,491 \cdot l^{-0.5}}{T}\right)} \tag{6}$$

where D is the moisture diffusion coefficient (expressed in m^2/s), T is the operation temperature in K, c is the local moisture concentration of the insulation (expressed in % of dry weight) and (l) is the insulation thickness expressed in millimetres.

It is interesting to note that the liquid that impregnates the cellulose has an important role in the diffusion coefficient of water. Figs. 5 compare the moisture diffusion coefficients for a piece of cellulose insulation of thickness 3mm impregnated with mineral oil and with the natural ester Fig. 5 (a) shows the dependence of both coefficients with temperature for moisture concentration 1 % and Fig 5 (b)shows the dependence with the moisture content of the cellulose insulation at 70 °C.



(a) Moisture concentration in cellulose 1%.



(b) Temperature 70 °C.

Fig. 5. Moisture diffusion coefficient for a piece of solid insulation of thickness 3 mm.

As it can be seen, both moisture diffusion coefficients increase with the moisture concentration and with the temperature, being the coefficient of mineral-oil-impregnated paper considerably lower than that of natural ester-impregnated insulation. This implies that the diffusion of moisture inside the solid insulation will be slower in the case of a mineral-oil-impregnated transformer and then the duration of the moisture transient processes will be higher too.

To model the moisture dynamic process in a cellulose-oil system it can be assumed that the surface of the paper reaches the equilibrium with the oil in an instantaneous way, and thus, at every iteration, the paper surface is considered to have a moisture content equal to the C_{equil} obtained for the temperature of this particular time instant.

The boundary considered to solve Fick's equation (C_{equil}) is calculated at each iteration using the moisture equilibrium curves experimentally obtained (Fig 4), and considering the temperature of the analysed part of the insulation and an additional mass balance equation (7) that assumes the total weight of water in the transformer does not vary during the simulation time, although the mass of it is splits between paper and oil in different proportions as temperature changes.

$$W_{total} = M_{cellulose} \cdot \frac{C_{equil}}{100} + M_{oil} \cdot \frac{PPM_{oilequil}}{1,000,000} \tag{7}$$

where W_{total} is the total mass of water in the transformer, expressed in kg, $M_{cellulose}$ is the mass of cellulose, expressed in kg, M_{oil} is the mass of oil, expressed in kg, C_{equil} is the final % weight of water in cellulose and $PPM_{oilequil}$ is the moisture content in oil.

Once set up the boundary condition, the model solves Fick's equation at each iteration (4) using to this end the finite element method. The output of this calculation is the moisture distribution throughout the solid insulation at each iteration. The average moisture in paper C_m, is then calculated using equation 8.

$$C_{m-est(t_i)} = \frac{1}{l} \int_{x=0}^{x=1} C_{est(x,t_i)} \cdot dx \tag{8}$$

where l is the solid-insulation thickness in metres.

4 Case studies

In order to evaluate the moisture migration processes in a transformer filled with a natural ester, and to compare it with the processes that would take place in a transformer filled with mineral oil subjected to similar operating conditions, several cases have been simulated with the dynamic model that was proposed in [26] and summarized in the previous section.

The simulations consider a certain thermal profile and calculate the moisture dynamics in the oil-paper insulation according to it. The insulation thickness considered for the simulations was 3 mm and the initial moisture content was of 4 %.

The thermal profiles considered in this section were calculated using the thermal model of IEEE Std C.57.91-2011 for different load profiles. Although the temperature distribution that would be established in a transformer insulated with an ester would be different to the distribution in a transformer insulated with a mineral oil (because of differences in the viscosities of both fluids and differences in the cooling systems of ester-filled transformers), we have decided to consider identical temperatures for both cases to facilitate the comparison of both types of scenarios.

4.1 Case 1. Load step

The first case considers the temperature profile shown in Fig. 6. This temperature profile was calculated with the thermal model of IEEE Std C.57.91-2011 considering a load step.

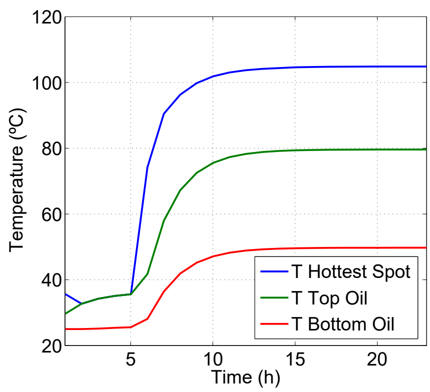


Fig. 6. Temperatures distribution for case 1.

4.1.1 Moisture dynamics in a transformer insulated with a natural ester

Fig. 7 shows the moisture contents of paper and oil that would be attained in steady state condition for every operating temperature if the insulating fluid were the natural ester Biotemp. As was expected, as temperature rises there is a migration of moisture from paper to oil, so the oil moisture content tends to increase while the cellulose moisture content decreases. However, as explained before, the dynamics of moisture of the oil-paper insulation has a large time constant, and the instantaneous values of moisture in the cellulose and the oil are not the steady state ones but the ones shown in Fig. 8.

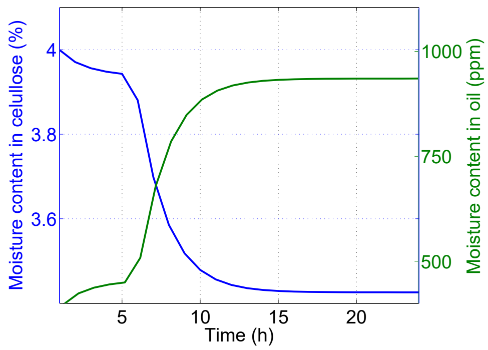


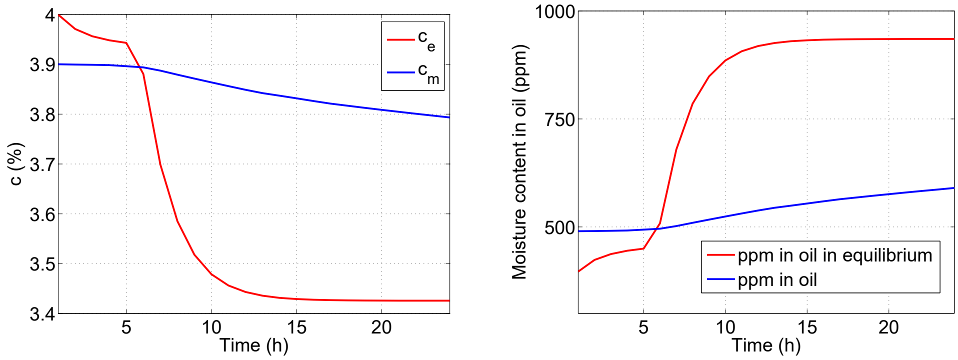
Fig. 7. Moisture content in the natural ester and the cellulose insulation in steady state obtained from moisture dynamic model in case 1.

Fig. 8 (a) shows the instantaneous moisture content inside the cellulose during the operation cycle (c_m), and the moisture content that would be attained for each temperature if the system would be in steady state (c_e). The behaviour observed is that while the temperature increases the moisture content in cellulose starts to decreasing towards the equilibrium condition. As it can be seen, the evolution of the instantaneous moisture of paper and oil towards the equilibrium is slow and equilibrium is not reached even after 24 hours of simulation.

Fig. 8 (b) shows the moisture content in the natural ester during the operation cycle and the moisture content that would be attained in steady state conditions. Opposite to the cellulose, the moisture content in oil increases with the temperatures. According to the Fig. 8 (b), the moisture content in oil keeps increasing until reaching the equilibrium.

4.1.2 Comparison with the moisture dynamics in a transformer insulated with a mineral oil

If the same temperature profile is applied to a transformer insulated with mineral oil, the main difference that can be noted is the high absorption capacity of the natural ester compared to the mineral oil. Fig. 9 (a) shows the moisture

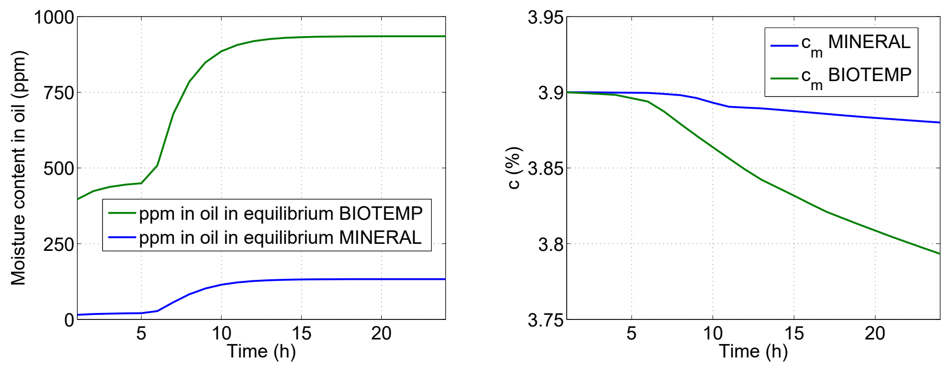


(a) Cellulose. (b) Natural ester.

Fig. 8. Steady state moisture vs. instantaneous moisture when the insulating fluid is a natural ester. Case 1

content in the natural ester and the mineral oil in steady state. As it can be seen, the values of moisture are more than nine times higher in the natural ester than in mineral oil at high temperatures. Since the solubility of these kinds of oils increase with the temperatures, natural esters can extract much more water from cellulose at the same temperature than a mineral oil.

On the other hand, all the conditions explained above can be evidenced looking at the evolution of the instantaneous moisture content in cellulose when both kinds of fluids are used (Fig. 9 (b)). It is noted that the moisture migration rate, which is reflected by the slope of the curves, is higher in the system insulated with natural ester. This is due to the differences on the diffusion coefficients of both materials and the differences in the equilibrium point.



(a) Ppm oil steady state. (b) Instantaneous moisture cellulose.

Fig. 9. Comparisson of the moisture dynamics if the insulating fluid is mineral oil or natural ester. Case 1

4.2 Case 2. Cycle load proposed in IEEE Std C.57.91-2011

In the second case, the temperature profile shown in Fig. 10 is considered. This temperature profile has been obtained applying the thermal model proposed in IEEE Std C.57.91-2011 to the analysis of the temperatures of the transformer when a cycle load is considered. As it can be seen the temperatures in the transformer follow a cyclical behaviour.

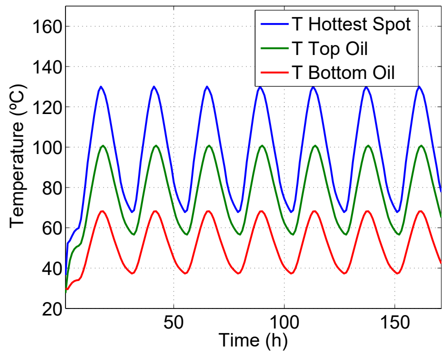


Fig. 10. Temperatures distribution calculated for case 2.

4.2.1 Moisture dynamics in a transformer insulated with a natural ester

Fig. 11, shows the moisture contents that would be attained in oil and paper for each working temperature if the system would be in steady state. As it can be seen these steady state moistures vary in a cyclical manner as well, following the moisture migration phenomena imposed by temperature changes explained in Section 2.

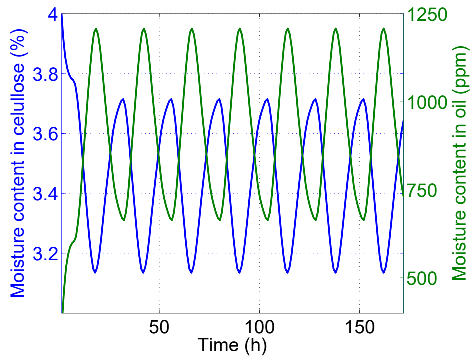
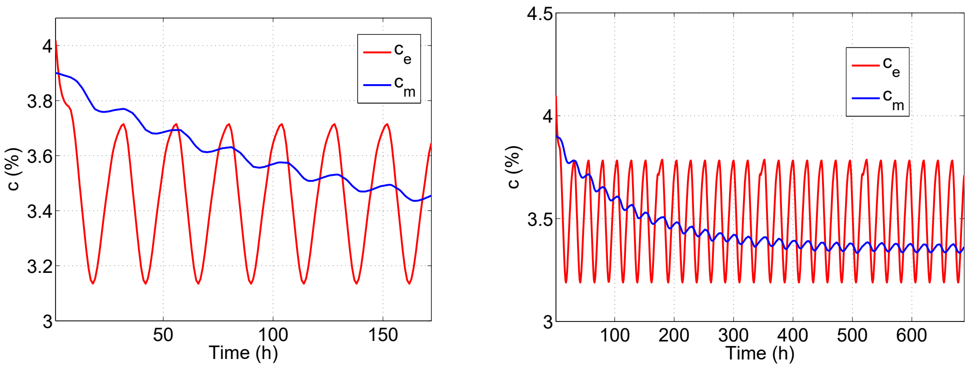


Fig. 11. Moisture content in the natural ester and the cellulose insulation in steady state obtained from moisture dynamic model in case 2.

In Fig. 12 (a), the value of the instantaneous average moisture of the cellulose is shown. Instantaneous moisture also changes cyclically with the temperatures although, as it can be seen, it presents a downward trend. This trend is due to the fact that the diffusion coefficient depends on temperature, hence the desorption of moisture from paper to oil (which occurs when the temperature increases) takes place at a higher rate than the process of adsorption of moisture by cellulose that takes place when temperature decreases.



(a) One week.

(b) One month.

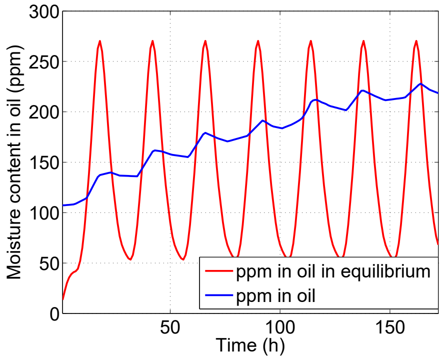
Fig. 12. Moisture content in cellulose in operation (c_m) and steady state (c_e) obtained from moisture dynamic model in case 2.

Fig. 12 (b) shows the values of the instantaneous and steady state moistures in the cellulose after one month of operation. As it can be seen the instantaneous moisture varies cyclically during the whole period and the instantaneous average value of moisture in cellulose reaches a stable condition after approximately 400 h of operation.

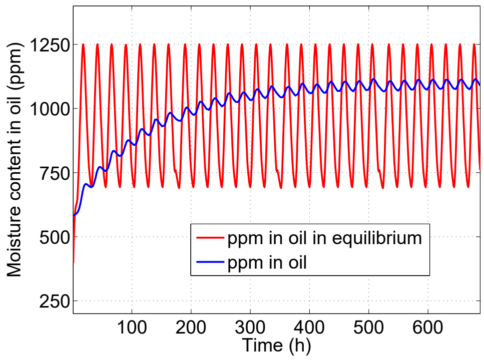
Likewise, Fig. 13 (a) compares the instantaneous moisture content in the fluid during the operation cycle and the moisture content of oil in steady state. Despite the moisture content is changing cyclically with temperature, it has a trend to increase because the rate of the absorption in oil is higher than the rate of return to cellulose. This trend keeps constant until the equilibrium is reached. Fig. 13 (b), shows the moisture content of the fluid after one month of operation under cyclical load.

4.2.2 Comparison with the moisture dynamics in a transformer insulated with a mineral oil

The same temperature profile was considered for a transformer insulated with mineral oil. Fig. 14 compare the instantaneous moisture content in the cellulose in both cases. As it can be seen the decreasing trend is observed in both cases although in the mineral oil the desorption is much slower than in the natural ester.

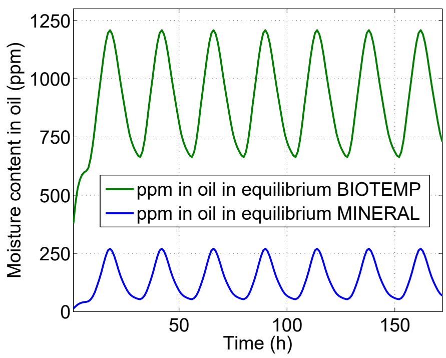


(a) One week.

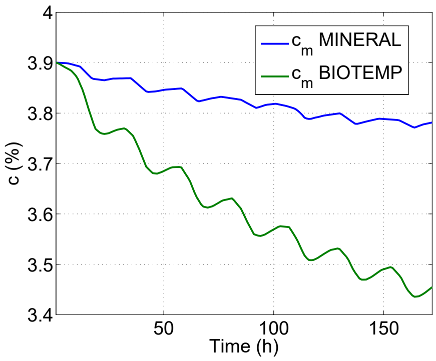


(b) One month.

Fig. 13. Moisture content in the natural ester in operation and in steady state, obtained from moisture dynamic model in case 2.



(a) Ppm oil steady state.



(b) Instantaneous moisture cellulose.

Fig. 14. Comparisson of the moisture dynamics if the insulating fluid is mineral oil or natural ester. Case 2

4.3 Case 3. Overload and sudden disconnection

For the third case a long term 1.5 p.u. overload was considered, followed by a sudden disconnection of the transformer. This case has been reported to be specially critical when highly wet transformers are operated at low ambient temperatures. A constant ambient temperature of 5 C was considered to obtain the thermal profile shown in Fig. 15. It is very unlikely to find temperature profiles as extreme as the one presented in this case, however the reason to simulate this case were based in the importance to get insight about the saturation phenomena.

4.3.1 Moisture dynamics in a transformer insulated with a natural ester

When the transformer is strongly overloaded, the temperature of the insulation rises to very high values and at the same time the oil becomes more

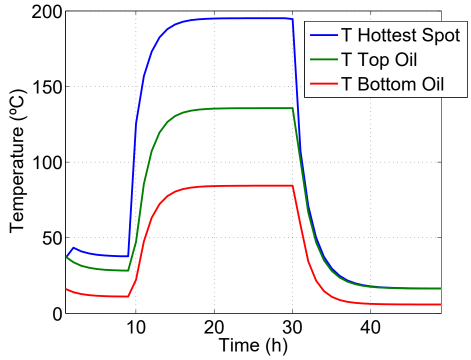


Fig. 15. Temperatures distribution calculated for case 3.

hydrophilic, i.e. its solubility increases, and part of the moisture of paper migrate towards it. The migration rate is governed by its very high diffusion coefficient, and therefore the oil becomes able to admit a big amount of water. In consequence moisture migrates from paper to oil with a relatively fast migration rate, as the diffusion coefficient depends exponentially on the operating temperature.

As in the previous cases the steady state moisture in oil (shown in Fig. 16 (a)) increases with the temperature while the moisture content in paper decreases. It is important to note that the the temperature profile studied in this case, considers twenty hours of operation at very high temperature and during this time the migration of moisture from cellulose to the oil is much higher than in previous cases.

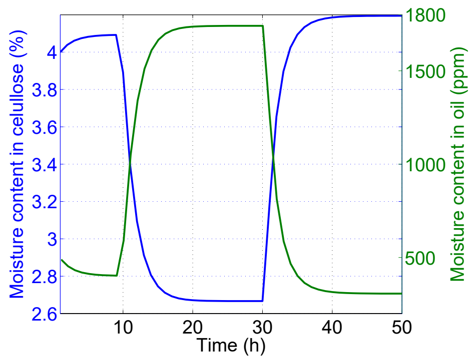
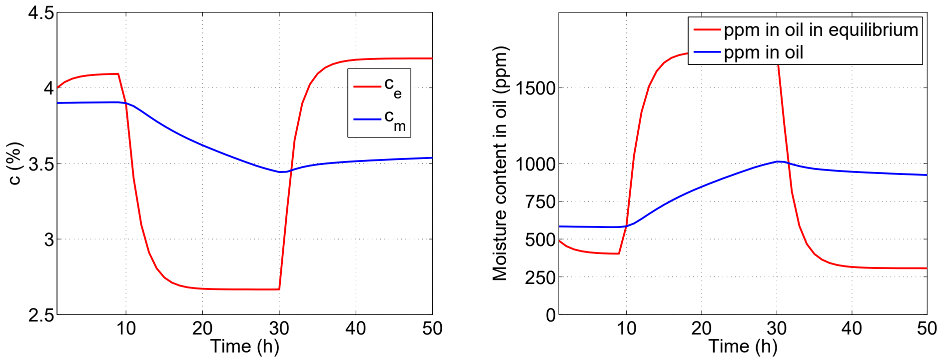


Fig. 16. Moisture content in the natural ester and cellulose insulation in steady state for Case 3.

Furthermore, Fig. 17 (a) shows the instantaneous moisture in cellulose during the simulated period, where the three stages of the thermal cycle have a clear impact in the simulated moisture contents. There is a first stage in which the instantaneous water content remains constant (hours 0 to 10), after ten hours the temperature rises abruptly and water starts to be released from the cellulose at a fast rate. It should be noted that the high value of temperature will make the diffusion coefficient to be high and then the rate of migration of water from paper to oil will be much higher that in the previous cases. After thirty hours of operation, the transformer is disconnected and the temperatures start to decrease rapidly. In this part of the cycle the moisture content of the cellulose increases again, although as the temperature is lower the diffusion process is slower and the increase of moisture is smooth.



(a) Cellulose. (b) Natural ester.

Fig. 17. Steady state moisture vs. instantaneous moisture when the insulating fluid is a natural ester. Case 3

Fig. 17 (b), shows the moisture content in the natural ester during the operation cycle and the moisture content in steady state, the moisture content in oil increases with the temperatures and viceversa looking for reach the equilibrium, as it is explained above for the load profile used in this case neither the moisture content in paper nor moisture content in oil reach the equilibrium.

Fig. 18, shows the instantaneous moisture in oil and the saturation limit, which is the maximum amount of moisture accepted by oil without being satured. The saturation limit depends on temperature and can be calculated according to equation 9. As it can be seen, after disconnection of the transformer, there is a certain risk of saturation of the oil due to the slowness of the migration process and an increased saturation limit driven by the low temperature caused by the disconnection. This would cause the presence of water in liquid phase within the transformer tank [7] which is a hazardous situation.

$$LogW_S = 5.67 - \frac{791}{T} \tag{9}$$

4.3.2 Comparison with the moisture dynamics in a transformer insulated with a mineral oil

The same load conditions were applied to simulate the moisture dynamics of a transformer insulated with mineral oil under these conditions. The moisture content in the two kinds of oils and cellulose can be observed in Figs. 19 (a) and (b) respectively.

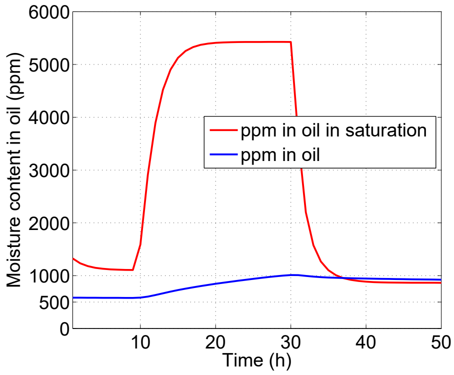
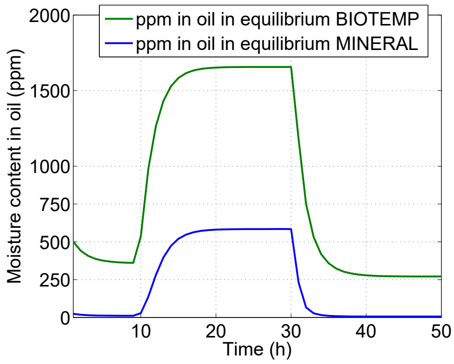
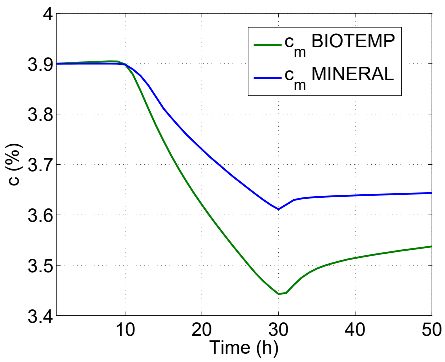


Fig. 18. Moisture content in the natural ester in saturation vs instantaneous moisture. Case 3.



(a) Ppm oil steady state.



(b) Instantaneous moisture cellulose.

Fig. 19. Comparisson of the moisture dynamics if the insulating fluid is mineral oil or natural ester. Case 3

Figs. 18 and 20 show the saturation condition for the two kinds of oils.

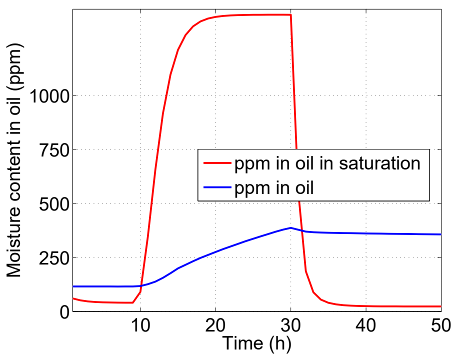


Fig. 20. Moisture content in mineral oil in saturation. Case 3.

In all cases, the moisture content in the natural ester is higher than in mineral oil. However, in this case is interesting to observe the difference in the saturation conditions of both kinds of oils. After the disconnection (30 hours), the mineral oil reaches saturation levels higher than those of the natural ester

(Fig. 18). This is due to a double effect. On the one hand, the saturation limits of natural esters are much bigger that those of natural oils (see equations 9 and 10).

$$LogW_S = 7.44 - \frac{1,686}{T} \tag{10}$$

Additionally, the diffusion coefficient is lower in mineral-oil impregnated insulation, and the return of water to the cellulose is, in consequence slower, which increases the risk of saturation of the oil in this condition.

5 Conclusions

In this paper a thorough discussion of the moisture dynamics of transformers insulated with natural esters is presented, where multiple load cases have been considered and analysed. To estimate the moisture migration process, a multi-physic model which had been previously developed and implemented was used, along with ester-cellulose and mineral oil-cellulose moisture equilibrium charts that were experimentally obtained in the lab. The moisture dynamics in the ester-cellulose system has shown consistency in all analysed cases; due to its greater affinity for water, combined with the hydrolysis phenomena occurring inside the transformer, water particles are forced to migrate from cellulose-based insulation to the natural ester in much larger quantities than in conventional mineral oil, this reaction is expected to take place at slower rates at lower temperatures. Future work will focus on experimental validation of the model, taking into consideration load data from transformers in real operation and values of initial moisture content other than the ones achieved in the lab. Moreover, a comparison with other insulating liquids, i.e Synthetic Oil is expected to cover the spectrum of the most typical insulating liquids used in the industry.

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