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A multiphysical model to study moisture dynamics in transformers

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***Abstract*—Moisture is one of the key variables that must be considered when determining the load profiles that can be safely applied to a transformer. On one hand the presence of high amounts of water accelerates the ageing rate of the transformer solid insulation, shortening the life expectancy of the equipment. Moreover, the dynamic processes of moisture migration between paper and oil must be considered in order to avoid a potential cause of failure, such as the formation of bubbles in the interface paper-oil, or the moisture saturation and subsequent formation of liquid water in oil. These processes are linked to the changes of temperature, however, within the transformer, both processes have very different time constants what complicates the analysis. In this paper a mathematical model is presented that allows us to study the moisture dynamics in a transformer. The model considers a multiphisical approach incorporating a thermal module and a moisture dynamic module what makes possible to analyse the behaviour of the moisture for a certain load profile. Some application cases are included in the paper to illustrate the model operation.**

I. Introduction

Power transformers are one of the most important components in electric systems. Knowing their condition is essential to meeting the goals of maximizing the return of the investment and reducing the total cost associated with transformer operation. In order to extend the life of the equipments while operating them with enough reliability, modern maintenance and operation should combine the use of predictive techniques and behaviour models which could assess the maximum load values that could be safely applied to the equipments considering their condition.

As it is well known, moisture has a strong influence on the performance of cellulose-oil systems in power and distribution transformers. An excessive water content accelerates the paper ageing, increases the presence of partial discharges and decreases the dielectric strength of the insulation. International standard IEEE 62-1995 [1], classifies the moisture contents that can be present in the liquid or solid insularion of transformers according to the condition of the equipment. In the case of moisture in oil, reference values use to be expressed as Relative Saturation values (RS) or parts per million of weight (ppm), while the advisable moisture content of solid insulation is generally expressed in percent of weight. According to [1], moisture contents above 30 % of RS in oil or 4.5 % in paper are considered to be excessive to operate a transformer safely. However several authors have pointed out that partial discharges and other dielectric problems can appear in transformers with lower moisture levels under certain working conditions [2].

Despite of the factory drying process all the transformers are subjected to as a final step of their manufacturing process, typical moisture contents in the solid insulation of new transfomers stil remain within a range 0.5-1 %. During transformer life those levels tend to increase because of the degradation of the molecular chain by thermal stresses and oxidative processes [3], or because of water ingress either via the conservator or through leaks in the tank. For those reasons it is common to find moisture levels above 4 % in weight in the solid insulation of transformers that have been in operation for more than 20 years, and also in newer transformers that have been subjected to certain operations, such as on-site repairs.

Because of the hydrophobic nature of oil and the hydrophilic character of cellulose, water is mainly absorbed in the transformer solid insulation [3] in a proportion that depends on the insulation temperature, the mass ratio of oil and paper insulation and the kind of insulating liquid in the transformer i.e mineral oil, natural or synthetic esters. However, this distribution is not static since as temperature increases the water solubility of oil increases while the adsorption capacity of cellulose decreases, and then a dynamic process takes place which forces water molecules to migrate from cellulose to oil. When temperature decreases, the process reverses and the solid insulation begins to take up water molecules back from the oil [3].

Although direct determination of the moisture content of transformer's solid insulation is not possible, because of the unfeasibility of taking paper samples from the transformer's active part, there are several indirect methods that can lead to a good estimation of this variable in field transformers. Some of these are based on the use of equilibrium charts [4], [5], which makes it possible the estimation of the water content of the solid insulation if the temperature and the water content of oil are known. Others are based in continuous monitoring of water in oil and dynamic modelling [6], [7]. Alternatively, the methods based in the determination of the dielectric response of the transformer insulation have been pointed out by Cigre as the most suitable to asses the moisture content of paper and pressboard [8]. Different approaches can be applied to determine the response of the insulation in the time domain, i.e. Polarization and Depolarization Currents Measure (PDC) and Recovery Voltage Measure (RVM), or in the frequency domain i.e. Frequency Dielectric Spectroscopy (FDS).

During the dynamic operation of transformers their temperature changes, because of load variations and changes on the ambient conditions; in consequence the moisture distribution will change as well, moving towards an equilibrium point which depends on the temperature, the geometry of the insulation and the moisture content of the system [7]. Several authors [9], [10], [11], [12] have previously obtained moisture-equilibrium-charts which represent the relationship between the moisture levels of oil and paper in equilibrium conditions at different temperatures. It should be noted that moisture migration processes involve large time constants and therefore moisture migration processes will not always be completed. In consequence, equilibrium curves should not be considered as a reliable tool to estimate the moisture content of solid insulation of an in-service transformer.

The behaviour of moisture inside the transformer insulation is a key aspect in loading studies, as there is a relationship between the moisture dynamics on a transformer and the load profiles that can be applied safely to it. 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 [2], [13], [14], [15]. In [14] 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 [2], 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. The authors validated this hypothesis by means of a thorough laboratory study and with FEM modelling. According to their results, the problem not only affects the transformers with very high moisture contents, but also those with medium (2-4%) moisture levels in the solid insulation.

Besides the dielectric aspect, the combination of high levels of moisture and high temperatures may have an great impact on the life expectancy of the transformer solid insulation. If the solid insulation operates with high humidity levels the ageing rate of the paper is higher [16], [17] and thus a lower hot-spot temperature would be acceptable to preserve the condition of the solid insulation.

In this work, a multi-physical model is proposed that combines the study of thermal and moisture dynamic phenomena in transformers. The model can be applied to the study of the dynamic behaviour of moisture within transformer insulation under different operating conditions, what is relevant for loadability studies.

The proposed model could be also be used as a part of integrated on-line monitoring systems that estimate the moisture content of cellulosic insulation from the measure of the moisture content of oil,using a simmilar methodology to the one proposed in previous works [6], [7] but incorporating a more accurate modelling for the diffusion of water in the cellulosic insulation and empirically-obtained parameters.

II. Moisture dynamics model

The objective of the model is to allow us the simulation of the moisture dynamic processes that take place in a transformer under certain working conditions. Considering a particular load profile and an estimated moisture content on the insulation, the model simulates how the distribution of moisture between the transformer solid and liquid insulation would evolve. By using those estimations, it would be possible either to identify critical points on the transformer operation or assessing on risks associated to a certain load profile.

The moisture dynamic model proposed in this work is an integration of the thermal model described in the Annex G of IEEE standard C57-91-2011 [18] and a moisture model based in the solution of Fick's second law with a set of dynamic boundary conditions [19], [20]. For the integration of these two models, the computational Finite Elements tool Comsol Multiphysics and the software Matlab were used.

A. Thermal model

The thermal model implemented in this work was taken from the literature, since extensive work on transformer thermal modeling has been carried out in the last decades by many authors, and several reliable models are available in technical literature and standards [21], [22], [23], [18].

IEEE standard C57-91-2011 [18] proposes two different methodologies to calculate the temperature distrubution throughout a transformer for a certain load profile. The simplest one, given in its Clause 7, is based in solving a first order differential equation that models the increase or decrease of temperature for a certain load profile. An alternate method is given in the Annex G of the same Standard [18] which accounts for changes in load loss and oil viscosity caused by changes in the resistance and oil temperature, and also considers the effect of a variable ambient temperature. The model of the Annex G was implemented in this work aiming at improving the accuracy for the calculation of the temperatures during transient loadings [18]. Nevertheless, any other thermal model could be applied to calculate the temperature profiles that are used as an input for the moisture dynamics module, which constitutes the main contribution of this work.

Although just a short summary of the implemented model is given below, a full description of the model and the whole set of implemented equations can be found in the Annex G of IEEE Std C57-91-2011 [18].

The adopted model [18] provides equations to calculate the temperatures at the winding hottest-spot and at the bottom and top of the oil, based on the principle of conservation of energy during a small period of time, Δt. The system of equations provided in the standard constitutes a transient forward-marching finite-difference calculation procedure. The equations are formulated so that temperatures obtained from the calculation at the prior time t_1 are used to compute the temperatures at the next instant of time $t_1 + \Delta t$ or t_2. Time is increased again by Δt, and the last calculated temperatures are used to calculate the temperatures for the next time step. At each time step, the load losses are calculated for the actual load and corrected considering the variation of resistance with temperature. Corrections for fluid viscosity changes with temperature are incorporated to the equations as well.

The hottest-spot temperature is made up of the following terms:

$$\Theta_{hs} = \Theta_{amb} + \Delta\Theta_{bo} + \Delta\Theta_{ho-bo} + \Delta\Theta_{hs-oil} \tag{1}$$

where Θ_{hs} is the winding hottest-spot temperature, Θ_{amb} is the average ambient temperature during the load cycle to be studied, $\Delta\Theta_{bo}$ is the bottom fluid rise over ambient, $\Delta\Theta_{hs-bo}$ is the temperature rise of oil at winding hottest-spot location over bottom oil and $\Delta\Theta_{hs-oil}$ is the winding hottest-spot temperature rise over oil close to the hottest-spot location (all of them expressed in $^{\circ}C$).

The temperatures of the top and bottom oil are determined from following equations:

$$\Theta_{bo} = \Theta_{avoil} - \frac{\Delta\Theta_{tr-br}}{2} \tag{2}$$

$$\Theta_{to} = \Theta_{avoil} + \frac{\Delta\Theta_{tr-br}}{2} \tag{3}$$

where Θ_{bo} is the bottom fluid temperature, Θ_{to} is the top fluid temperature, Θ_{avoil} is the average fluid temperature in tank and radiator and $\Delta\Theta_{tr-br}$ is the temperature rise of fluid at top of radiator over bottom fluid expressed in $^{\circ}C$.

Additionally, the model considers that the distribution of temperature on the transformer winding is linear, so temperatures at other heights of the winding could be estimated as well.

B. Moisture diffusion modelling

Moisture migration inside the cellulosic insulation is a complex process involving heat and mass transfer phenomena. However, as the thermal time-constant of a transformer is much smaller than the diffusion time constant, the desorption and adsorption of moisture from cellulose to oil can be modelled as a diffusion phenomenon by means of Fick's second law [24], [25]:

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

where *c* is the local total moisture concentration in cellulose (expressed in % of dry weight), *t* is the time (expressed in seconds), *x* is the distance into the material in the direction of the moisture migration (expressed in m) and *D* is the effective moisture diffusion coefficient in the solid insulation (expressed in m^2/s).

The diffusion coefficient is the parameter that characterizes the movement of water within the solid insulation. The adoption of an effective diffussion coeficient to describe the migration process consititutes a simplification, as the transport of moisture inside cellulose proceeds in the form of vapour and condensed water through the fibres and void spaces of the cellulose. However, considering the different transport methods would not be easily implemented [25] specially because of the practical complexity of determining adequate parameters for different materials.

Several authors have proposed expressions for effective diffusion coefficients of oil-paper insulating systems which can be applied to model the moisture migration processess in cellulosic materials [26], [27], [28], [29]. In this work, the diffusion coefficient obtained by the authors in a previous study [25] was considered (eq. (5)) which is valid for an insulating system based on kraft paper and mineral oil.

$$D = 2.5 \cdot 10^{-9} \cdot l^{4.3} \cdot e^{\left(0.2 \cdot c - \frac{3{,}164 \cdot l^{0.29}}{T}\right)} \tag{5}$$

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

The implemented model may consider either Kraft paper or pressboard as cellulosic insulation, by changing the considered expression of the diffusion coefficient to characterize each material. It can also consider several insulating fluids, as mineral oils or natural esters that are represented by adequate boundary conditions, as will be explained later.

As can be seen in eq. (5), the diffusion coefficient of cellulose depends on the moisture concentration in the material; in consequence Fick's equation becomes non-linear, what makes necessary to apply a numerical method to solve it. In this work Fick's equation was solved by means of the finite element method (FEM), using the commercial software Comsol Multiphysics 3.5a. The initial concentration of moisture and the temperature of the insulation were considered independent inputs to the diffusion model.

Fig. 1 shows a schematic of the implemented model. As the process of moisture migration occurs mainly in a unidirectional way [24] the moisture model considers a one-dimensional geometry to study the problem. In the particular case represented in Fig. 1, one of the sides of the insulation is considered to be in contact with the winding, and then no diffusion takes place on this side. Different scenarios and geometries could be studied by the model as, for instance, the diffusion within a pressboard barrier where both sides would be permeable to moisture.

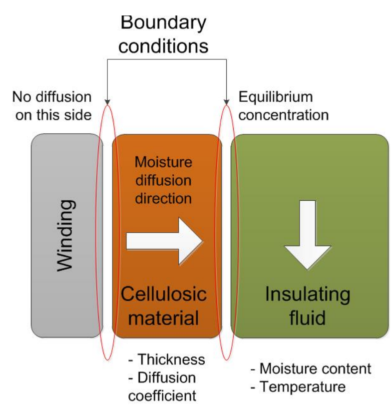

Fig. 1. Outline of the diffusion model.

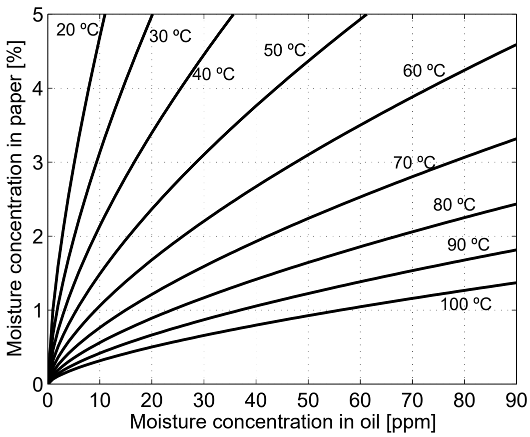

Fig. 2. Oommen charts

C. Boundary conditions

The boundary conditions should establish the moisture content on the interface between the solid and liquid insulation at each time.

The water adsorption and desorption at the paper-oil interface behaves as a convective process. Howe in [30] studied this process concluding that, as the water exchange on the paper-oil interface is much faster than the moisture diffusion processes within solid insulation. According to this result, the model assumes that the surface of the paper reaches the equilibrium with the surrounding oil instantaneously and takes the equilibrium concentration as a boundary condition.

To calculate the value of the equilibrium conditions the model makes use of Oommens's equilibrium charts, which calculate the partition of moisture between oil and paper as a function of temperature (Fig. 2).

To implement Oommens's charts in the model, the parametrization proposed by Fessler [31] was used. Thus, the moisture concentration in paper is calculated using eq. (6):

$$C_{equil} = 2.173 \cdot 10^{-7} \cdot p_v^{0.6685} \cdot \exp\left(\frac{4725.6}{T}\right) \tag{6}$$

where p_v is the moisture partial pressure that can be calculated from the oil relative humidity RH as

$$p_v = RH \cdot p_{v,sat} = \frac{ppm}{ppm_{sat}} \cdot p_{v,sat} \tag{7}$$

where ppm, is moisture concentration in oil expressed in parts per million and ppm_{sat} and $p_{v,sat}$ are moisture concentration and partial pressure in saturation condition [9]. The partial pressure of the saturated water is obtained by the correlation proposed by Foss in [32], and the moisture concentration can be obtained from eq. (8).

$$\log(ppm_{sat}) = A - \frac{B}{T} \tag{8}$$

The parameters A and B in eq. (8) depend on the type of oil considered in the study and of its ageing conditions. The values $A = 7.09$ and $B = 1567$, which are typical data of a mineral oil, have been used to simulate the cases presented in this paper.

An additional mass balance equation is needed to determine the moisture concentration of paper in the equilibrium condition for a particular temperature (eq. (9). This equation, which was proposed by Frimpong in [33], assumes that the total weight of water in the transformer does not vary although the mass of it is splits between paper and oil in different proportions as temperature changes.

$$W_{total} = M_{cellulose} \cdot \frac{C_{equil}}{100} + M_{oil} \cdot \frac{PPM_{oilequil}}{1,000,000} \tag{9}$$

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.

III. Application of the Model

A. Model's implementation

Fig. 3 shows the flow chart of the proposed model. The transformer load profile and ambient temperature are provided to the model as input data, then the transformer operating temperatures are calculated using IEEE thermal model. The obtained temperatures are used for the simulation of the moisture dynamics inside the transformer. From the thermal profile, the instantaneous diffusion coefficient and the boundary conditions are calculated at each instant of the simulation.

Then the equilibrium moistures in paper and oil are calculated by solving the system of equations formed by 6 and 9. Although the equilibrium moistures would be only reached if the transformer operates at constant temperature for a very long time, those values are used as boundary conditions.

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, i.e. the model assumes that the surface of the paper reaches the equilibrium with oil in an instantaneous way. The model solves Fick's equation using the finite element method with the calculated boundary condition, and calculates the moisture distribution throughout the solid insulation at every iteration. The average moisture in paper C_m, is then calculated using eq. (10).

$$C_{m-est(t_i)} = \frac{1}{l}\int_{x=0}^{x=1} C_{est(x,t_i)} \cdot dx \tag{10}$$

where l is the solid-insulation thickness in metres.

Once calculated C_m, the instantaneous moisture content in oil can be also calculated using eq. (9).

As mentioned before, the model considers a one-dimensional geometry, what means that it calculates the distribution of moisture at a particular height of the insulation. However, the moisture distribution at different spots 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.

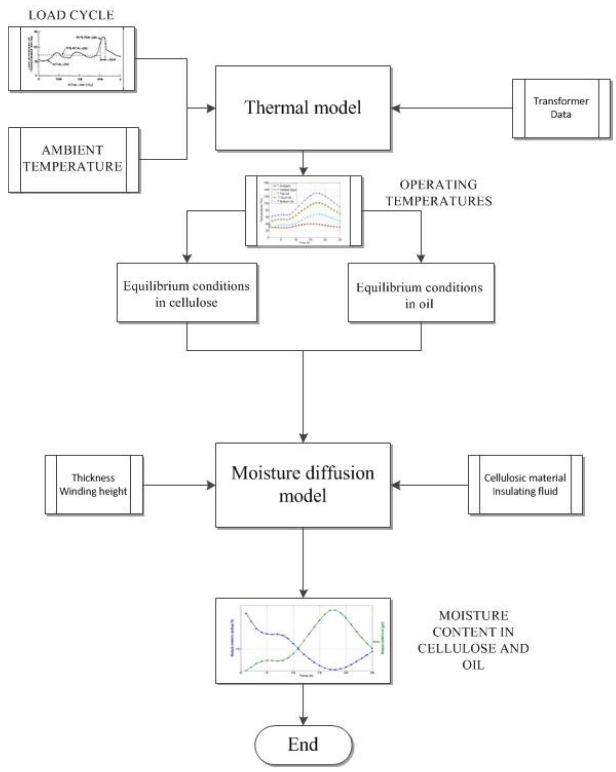

Fig. 3. General scheme of the moisture dynamic model.

The application of the model to the evaluation of the admissible load on a transformer starts from the premise that the transformer operator has an estimation of the moisture content along the transformer solid insulation. This estimation can be derived from dielectric-response measures or from the measures of a water-activity probe in combination with modelling.

The operator of the transformer can run simulations to analyse the temperature profile and the moisture dynamic processes that would take place in a particular region of the transformer insulation if a certain load profile is applied. With the results of the model, several critical points can be identified, such as excessive moisture in the liquid insulation with the subsequent risk of partial discharges, breakdown or even water saturation and formation of water in liquid state. The evolution of the moisture distribution of the solid insulation could also be used to identify local points with high moisture and subjected to high temperatures where excessive ageing of paper might take place [16]. Those analysis can help to take decisions on whether the application of this load factor is safe taking into account not only the thermal factor, but also the moisture dynamics aspects.

B. *Limitations of the model and sources of error*

In order to establish the validity of the proposed model and to facilitate the interpretation of its results, it is important to state what cases can be simulated with it and to understand the possible sources of error that can appear when applying it to the estimation of the moisture dynamics of a region of the insulation.

At its present version, the model is capable to analyse simple geometries consisting of one type of insulation and the insulating fluid at its interface. The model could simulate the migration of moisture on pieces of paper or pressboard of different thickness, located at different heights of the winding and impregnated with different insulating fluids (i.e. mineral oil or ester-based liquids). In order to obtain a simulation of the moisture dynamics of this region of the transformer, the user should estimate the initial moisture content of oil and the distribution of moisture in the region of the solid insulation that is going to be analysed. However, the model is not able to analyse the interaction between the different regions of the transformer. Certain error can be induced for not taking into account that the insulation of a transformer consists of cellulose parts of various thickness that are subjected to different temperatures, where the water will first migrate from thin paper to oil increasing its water content and thus slowing down the migration from pressboard to oil.

A global analysis of the moisture dynamics in the transformer with FEM would require the implementation of a fluid-dynamics module to describe the movement of the insulating fluid through the transformer considering the contribution of the different regions of the insulation to its moisture content. The difficulty of a model like that is that it would require considering a 3D geometry and thus great computing resources.

Another aspect that could induce to certain error is the fact that the hygroscopicity and the diffussion coefficient of water in a cellulosic insulation depend on the material's aging degree; the solubility of the insulating fluid also depends on its condition. These factors have influence on the moisture equilibrium curves and on the water distribution of the insulation [34]. This source of error could be avoided by using appropiate diffussion coefficients and equilibrium curves for each analysed situation. Some applicable values can be found in the literature [35], [34], [36].

Finally, it must be considered that although incorporating a thermal model would reduce the infrastructure of temperature-measuring sensors for a practical application, thermal modelling could lead to some error that might be reflected on the instantaneous moisture concentration of cellulose and oil calculated by the model. In [37] Susa presents an experimental validation of IEEE Std C57-91-2011 (Annex G) model under different loading situations, concluding that the model is able to calculate the temperature distribution with accuracy (i.e. with error below 5%), specially for load factors above 50 %. It must be noted that a few degrees of error in the estimation of the temperature will have very little impact on the estimations of the moisture-migration model.

Despite the limitations of the model, the incorporation of a model-based approach to the analysis of the moisture-migration related processes can lead to a more accurate image of what would happen in the transformer for a certain load profile. This can provide a more reliable decision-making system compared to previously published works [14].

IV. Case studies

The moisture dynamics model proposed in this work has been applied to the analysis of two practical cases, considerig to this end the specifications of a 52,267 KVA transformer which is defined in IEEE Std C57-91-2011 [18]. The constructive details and other parameters of the transformer are shown in Table I.

TABLE I
CONSTRUCTIVE DETAILS OF THE TRANSFORMER.

Parameters	Value
Refrigeration	ONAN/ONAF
Power	52,267 kVA
Core and coil weight	75,600 lb
Tank and radiators	31,400 lb
Gallons of oil	4,910
No load loss	36,986 W
Load loss	72.768 W
Total loss	109.755 W
Total mass of cellulose	3,023 kg
Total mass of oil	31,500 kg

The analysed geometry was a piece of insulation of thickness 3 mm, constituted of Kraft paper with a moisture content 4 per cent in weight, what would correspond to a transformer with a high level of moisture. The temperature considered for the simulations presented below was the top-oil temperature. The diffusion of moisture is considered to be one-directional as would be the case of the moisture migration on the insulation of transformer windings.

Two different loading profiles were simulated: A daily cyclical load and an emergency overload followed by a disconnection of the transformer. In each case the temperature profiles were simulated and used as an input for the moisture migration module.

A. Cycle load

In the first case, the load profile and the ambient temperature shown in Fig. 4 were considered. This profile is provided in the Annex G of IEEE Std C.57.91-2011 [18] as an example of cyclical short-term overload. The temperatures in the transformer (Fig. 5) follow the same cyclical behaviour as the load with an approximated time delay of two hours. That delay is due to the thermal time-constant of the transformer, which mainly depends on the masses of oil and paper in the transformer. The hot-spot temperatures reached at some instants of the simulated period are higher than 100 $^{\circ}C$ and so the loss of life of the insulation during these periods would be significant.

Fig. 6, 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 can be seen they vary cyclically as well. If the peaks of temperature and moisture are compared, it can be stated that the time delay between both variables is approximately one hour. redThis delay is due to the time-constant of the moisture-migration process inside the material, which is mainly dependent on the type of material considered and on the moisture concentration

Fig. 7 shows the value of the instantaneous average moisture of the cellulose, that, as can be seen follows the same cyclical pattern as temperature but with a downward trend. This is due to the fact that the diffusion coefficient depends on temperature, and in consequence the desorption of moisture from paper to oil that takes place when temperature increases evolves at a higher rate than the process of adsorption of moisture by cellulose that takes place when temperature decreases.

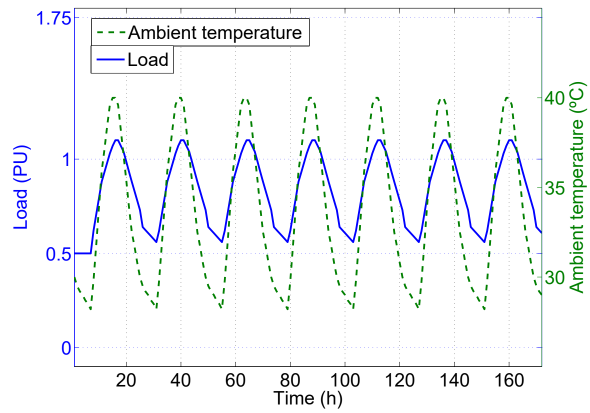

Fig. 4. Load cycle and ambient temperature used in case 1.

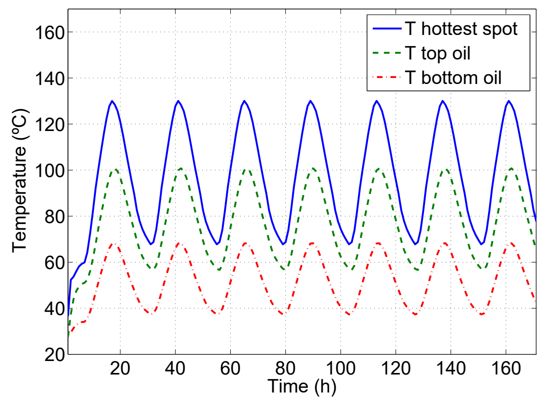

Fig. 5. Temperatures distribution calculated for case 1.

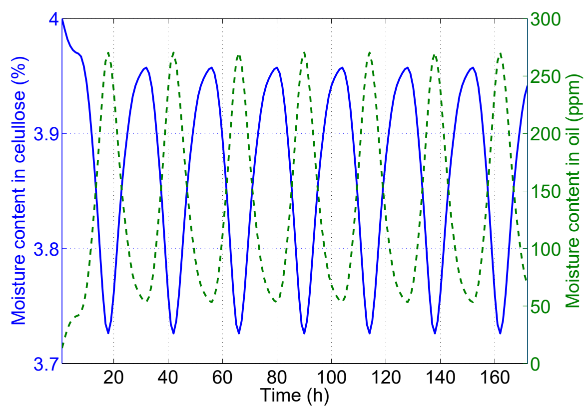

Fig. 6. Moisture content in MO and cellulose in steady state obtained from moisture dynamic model in case 1.

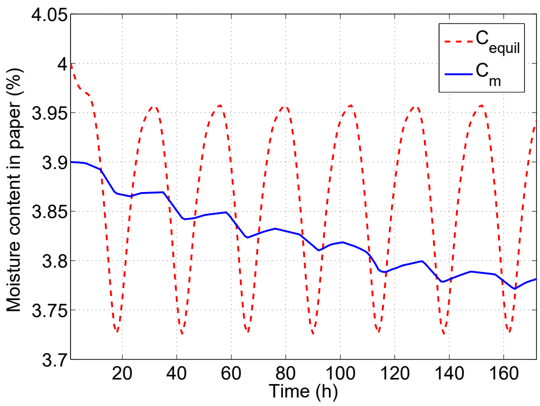

Fig. 7. Moisture content in cellulose in operation (C_m) and steady state (C_equil) obtained from moisture dynamic model in case 1.

Fig. 8 compares the instantaneous moisture content in oil during the operation cycle and the moisture content of oil in steady state. As can be noted, the observed pattern is complementary to that observed for the instantaneous moisture in paper.

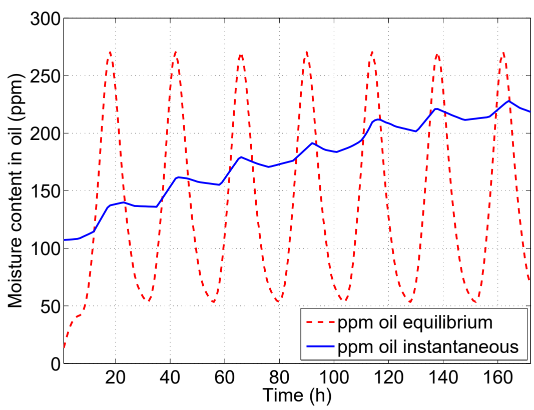

Fig. 8. Moisture content in MO in operation and steady state obtained from moisture dynamic model in case 1.

B. Overload and further disconnection

For the second case, a long term overload was considered followed by a sudden disconnection of the transformer. This case has been reported to be specially critical when wet transformers are operated at low ambient temperatures. The simmulated load profile and ambient temperature are shown in Fig. 9. As can be seen, a constant ambient temperature of 5 $^{\circ}C$ was considered during the simulation. It is very unlikely to find load factors as high as this in operating transformers, however the reason to choose this case is to get insight into the saturation phenomena warned about by several authors [38].

As can be seen in Fig. 10, when the transformer is so heavily overloaded the temperature of the insulation rises to very high values. At the same time, oil becomes more hydrophilic, i.e. its solubility increases and the oil becomes able to admit a high amount of water; then part of the moisture of paper migrates towards it. The migration rate is governed by the diffusion coefficient, which according to eq. 5 grows exponentially with temperature. Because of the high temperatures considered in this case the migration of water from paper to oil would be relatively fast.

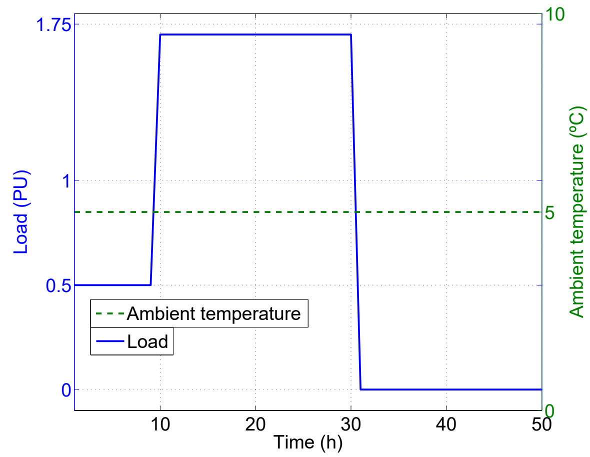

Fig. 9. Load cycle and ambient temperature used in case 2.

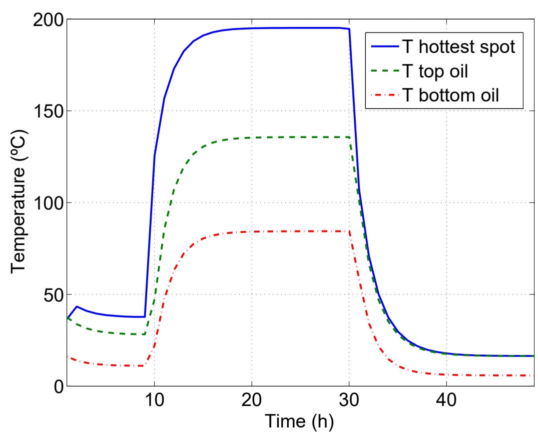

Fig. 10. Temperatures distribution calculated for case 2.

Fig. 11 shows the steady state moistures in oil and paper. As in previous cases, the steady state moisture in oil increases as temperature rises and decreases when it drops. The opposite happens with the steady state moisture in paper.

Figs. 12 and 13 show the instantaneous moisture contents in paper and oil obtained by the model. For the three load levels included in this case the behaviour of the moisture is as expected i.e moisture migrates from paper to oil when temperature rises and from oil to paper as temperature drops. When the load increases, the value of the average moisture of cellulose changes dramatically keeping a decreasing trend towards the equilibrium condition equilibrium. As can be seen, the migration of moisture from cellulose to oil during the overload period is sharper than that observed in the previous

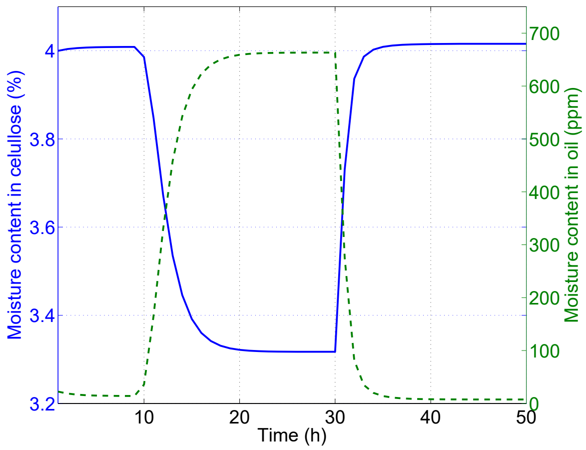

Fig. 11. Moisture content in MO and cellulose in steady state obtained from the moisture dynamic model in case 2.

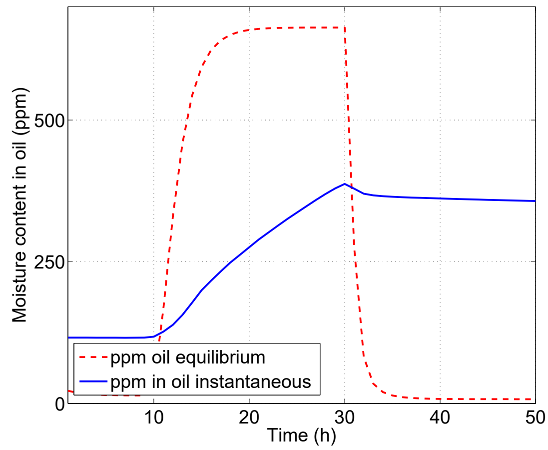

Fig. 13. Moisture content in MO in operation and steady state obtained from moisture dynamics model in case 2.

case; this is a consequence of the greater values of the diffusion coefficient obtained in those hours. After thirty hours of operation, the load changes to 0 PU, and in consequence the temperatures decreases. As this happens, the direction of the moisture flow reverts, and part of the moisture in oil starts to return to paper.

In Fig. 14 the instantaneous moisture content of oil is compared with the moisutre saturation limit (i.e. the maximum amount of moisture accepted by oil without being satured). The saturation limit depends on temperature and can be calculated according to eq. 8. As can be seen, after the disconnection of the transformer, the moisture of oil exceeds the saturation limit. This means that part of the water would precipitate and change into liquid phase what is a hazardous situation for the transformer [3].

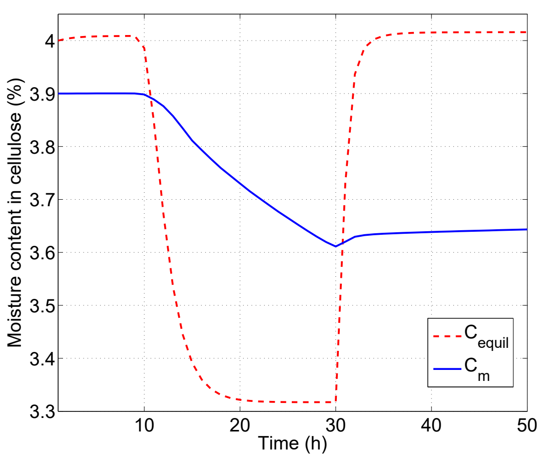

Fig. 12. Moisture content in cellulose in operation (c_m) and steady state (c_e) obtained from moisture dynamics model in case 2.

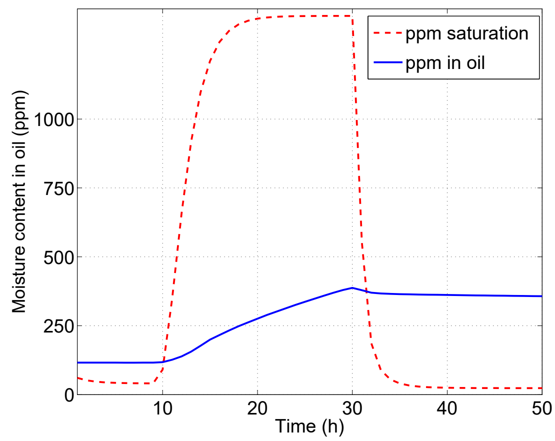

Fig. 14. Moisture content in MO in saturation vs instantaneous moisture. Case 2.

V. Conclusions

In this paper a moisture dynamics model is presented which is able to study of the behaviour of the moisture contained in the oil-paper insulation during the real operation of a transformer. The moisture content of oil and paper is estimated in a dynamic mode taking into account the temperature profile of the transformer. The proposed model is based on the integration of the thermal model proposed in the Annex G of the IEEE loading guide C.57.91-2011 [18], and a moisture model based on Fick's second law. The proposed model can be integrated in transformer dynamic rating systems, risk assessment programs and on-line moisture monitoring systems. As an example of the operation of the model, two practical cases are presented in the paper in which the model was used to simulate the moisture dynamic distribution under different loading profiles.

As a further work, the authors are working towards the experimental validation of the model using an experimental plant that emulates the temperature and moisture distribution of a service transformer [39].

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