IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 13, 2021, accepted October 31, 2021, date of publication November 8, 2021, date of current version November 12, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3125840

Experimental Validation of a Method of Drying Cellulose Insulation in Distribution Transformers Using Circulating Synthetic Ester

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This work was supported in part by the Polish National Center for Research and Development from the funds of Subactivity 4.1.2 ''Regional Research and Development Agendas'' entitled ''Mobile Insulation Drying System for Distribution Transformers Using a Liquid Medium'' under Project POIR.04.01.02-00-0045/17-00, the total value of the project is PLN 7 677 957, in part by the National Center for Research and Development under Grant PLN 6 084 569, and in part by the Polish Ministry of Education and Science under Grant 0711/SBAD/4456.

ABSTRACT The article concerns a method of drying cellulose insulation of distribution transformers with the use of synthetic ester. This method uses the high solubility of water in the ester compared to other dielectric liquids. The method is based on the striving of the oil-paper insulation system for a state of moisture equilibrium. Water migrates from the cellulose insulation of the high moisture content to the synthetic ester which is subjected to continuous drying. The research was carried out on a complex laboratory model reflecting the transformer insulation system. In this model, the drying of the ester was carried out using a molecular sieve with an appropriately selected adsorber weight. To check the drying efficiency of the cellulose insulation, the water content in the pressboard strips taken from the model, both before and after the drying process, was determined. The water content was measured using the Karl Fischer titration method. The research showed the high efficiency of the proposed method of drying. With the ester moisture in the range of 110-130 ppm and the insulation system temperature of about 70 °C, the loss of water in the samples dried for 7 days was over one percentage point. The obtained test results constitute the basis for the validation of the method on distribution transformers.

INDEX TERMS Power transformers, insulation, moisture, dielectric liquids.

I. INTRODUCTION

HV/MV distribution transformers are one of the most strategic and expensive components of the electric power grid. The transformers' lifetime, usually estimated by manufacturers to be around 30-50 years, depends mainly on the condition of the insulation system, which undergoes natural and progressive degradation processes during operation. In mineral oil, the rate of these processes is influenced, among others, by temperature. It is estimated that in the range from 60 °C to 100 °C, increasing the oil temperature by approx. 10 °C accelerates the aging processes twice [1]. Oxidation of oil also contributes to its degradation. However, it is possible to slow down this process by using oxidation inhibitors such as 2,6-di-tert-butyl-*p*-cresol (DBPC) and 2,6-di-*tert*-butyl phenol (DBP) [2]. Oil degradation processes lead to deterioration of electrical parameters and an increase in viscosity, acidity, and water content. In the case of cellulose insulation, aging processes are associated with the occurrence of three different chemical reactions, i.e. oxidation, hydrolysis, and thermolysis, the dynamics of which depend on temperature, the presence of oxygen, water, and catalysts. Cellulose oxidation reactions lead to the release of carbon monoxide, carbon dioxide, acids, and water. Water and acids are catalysts for the hydrolysis reaction, resulting in the depolymerization of cellulose. The oxidation and hydrolysis reactions take place in the entire operating temperature range of the transformer, and after exceeding 120 °C, the rate of the hydrolysis reaction is rapidly accelerated (over 2.5-fold increase in the hydrolysis reaction rate is observed in the range of 160-200 °C).

The associate editor coordinating the review of this manuscript and approving it for publication was Ali Raza.

Thermolysis reactions take place at temperatures over 120 °C and lead to the release of water, carbon dioxide, carbon monoxide, methane, acetylene, acetone, formaldehyde, furfural, furan, phenol, and other compounds in trace amounts. It should be emphasized that water is released in the oxidation reactions of both oil and cellulose, so it is a product of the aging of the whole oil-paper insulation system. Simultaneously, the water is a catalyst for the hydrolysis reaction leading to the depolymerization of cellulose. The moisture, in addition to the high operating temperature of the insulation system and the presence of oxygen, is the basic factor influencing the rate of aging processes in the transformer insulation. For example, cellulose paper with the moisture content of 3% will age 15 times faster than paper with a water content of 1% [3], [4]. In addition to aging processes, the cause of higher moisture may be the migration of water from the environment to the insulation system. This is due to the periodic pressure difference between the atmosphere and the interior of the tank and the relative humidity difference between the insulation system and the atmosphere. This problem especially applies to HV/MV distribution transformers, in which the conservator's construction allows air to come into contact with the oil (even if the air has been pre-dried by a dehumidifier).

High water content in cellulose insulation is one of the most serious threats to a transformer, as it has many negative effects. One of the risks is the depolymerization of cellulose, which leads to a deterioration of the mechanical strength of the insulation system. As a result, transformer windings are more susceptible to deformation, especially during short circuits accompanied by high electrodynamic forces [5]–[7]. The increase in the water content in the cellulose insulation also leads to a lowering of the critical temperature, at which the phenomenon of rapid release of water vapor bubbles may occur. The occurrence of this phenomenon in the transformer leads, on the one hand, to a sudden increase in pressure in the tank, and, on the other hand, to a significant reduction in the electrical strength of the insulation system in the area where gas bubbles are present. This can lead to turning off the transformer in a short time or a catastrophic failure. The increase in water content in the transformer insulation system causes a significant decrease in its electrical strength, the highest decrease is observed for moisture above 2% [8].

The high moisture level can result in the initiation of surface discharges and creeping sparks. Such discharges usually endanger the lower parts of the main insulation in the form of barriers and angular rings, where there are high values of the tangential component of the electric field strength to the surface of the pressboard elements. The temperature in these areas is relatively low, which means that the water content in the pressboard elements is high. Critical values of the tangential component of the electric field may appear there already at operating voltage [9], [10]. Another problem is the process of water migration from moist cellulose to oil, which reduces the ignition voltage of partial discharges and increases their intensity [11]. Moreover, when the heated, oil of the high moisture saturation comes into contact with the strongly cooled surface of the heat sinks, dissolved water condenses, which dramatically lowers its electrical strength.

Based on many years of research carried out by the authors on the moisture content of large power transformers with a capacity above 100 MVA, it follows that after 35 years of operation, their average moisture content is approx. 2% [12]. Similar test results were obtained in the case of distribution transformers with a capacity of 16 to 40 MVA, for which, after 35 years of operation, it can be also expected an average moisture content of cellulose insulation at the level of 2% (Fig. 1).

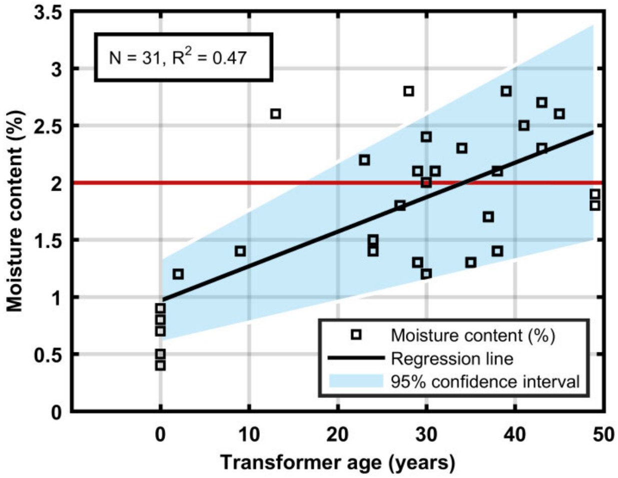

FIGURE 1. Moisture content in the insulation of distribution transformers depending on their age.

One of the ways to extend the service life of a transformer with an insulation of high moisture content is its on-site drying. Currently used methods of transformer drying require heating the insulation and creating a vacuum in the tank. The insulation can be heated by hot air, hot oil, and direct current (DC) or low-frequency current (LFC) flowing through the windings. The method of heating both windings with low-frequency current (LFH – Low Frequency Heating) under vacuum conditions is currently considered the best. Unfortunately, its applicability for HV/MV distribution transformers is very limited. Most problems are caused by obtaining an appropriate vacuum, mainly due to the tank leakage and its insufficient mechanical strength to compression [13]–[15].

II. METHODS OF CELLULOSE INSULATION DRYING

A. DRYING METHODS–STATE OF ART

Drying cellulose insulation is a very important problem, both at the stage of production and operation of the transformer [15]. Nowadays, the moisture of cellulosic materials after the production process should not exceed 1%, but the water content in very well dried insulation is even lower than 0.5% [16], [17].

Drying the transformer during its operation is a relatively new problem. It appeared when some transformers, mainly in Western Europe, reached the age of 30. With the increasing number of failures leading to explosions and fires, the problem was taken up by electric power grid operators.

The basic division of drying methods is made according to the place where the procedure is conducted. In the factory, drying is carried out in a stationary dryer, while mobile systems are most often used in operation.

The stationary drying system is of course used in the case of drying new transformers and transformers in operation, the condition of which is so bad that it requires a general overhaul. The use of a stationary dryer ensures high efficiency of drying but requires the transport of the unit from the electric power station to the repair plant, which is associated with high costs and the risk of damaging the transformer during transport.

The mobile drying system is used in the revitalization of units with the insulation of high moisture content but in good general condition.

Drying techniques in stationary and mobile systems are based on the same physical phenomena, but the procedures can differ significantly.

The methods that can be used in the mobile system include:

1) Drying by circulating hot oil subjected to continuous drying under vacuum.
2) Drying in a high vacuum environment.
3) Drying with hot air.
4) Drying with hot oil and vacuum.
5) Evaporative drying with the use of a special solvent and vacuum.
6) Drying consisting in heating the windings with low frequency current in a vacuum environment.

Drying with circulating hot oil that is continuously dried under a vacuum is one of the oldest methods. Unfortunately, this method is inefficient. The drying is based on water migration from the cellulose to the oil until moisture equilibrium will be achieved. The moisture equilibrium curves of the oil-paper system, for temperatures from 0 to 100 °C, have been developed i.a. by Oommen [18]. The amount of dissolved water in mineral oil in the equilibrium state is very small, hence the very low efficiency of the method.

The use of vacuum allows for better effects than those described above but in turn, it is difficult to ensure the tank tightness, especially in the case of old units. Another disadvantage is the inability to raise the temperature of the dried insulation.

In the past, attempts have also been made to dry the transformer insulation using hot air. This method does not require the tightness of the tank, but the problem is to ensure that the insulation is evenly heated. If the air is overheated, the ignition of oil vapors may also occur [19]. Currently, this method, combined with a vacuum, is used to pre-drying of insulation. A more effective method of heating the insulation turned out the heating with hot oil. After heating, the oil is drained from the transformer tank and a vacuum is applied. As a result of dynamic water evaporation, the insulation system cools down quickly and the process of heating the insulation with oil must be repeated many times, which is a disadvantage of the method [20], [21].

A breakthrough in the field of drying procedures was the evaporation method, which consists in using the heat of condensation of a solvent vapor for drying. This liquid has a composition similar to aviation fuel. A vacuum of about 7 mbar is generated in the tank, and then the solvent vapor at a temperature of 130 °C is introduced. The solvent condenses immediately on the cold insulation causing it to warm up. Solvent vapors reach all parts of the insulation, ensuring that they are evenly heated. In the next stage, a high vacuum is created in the tank, which causes an effective release of water from the insulation. This procedure has to be repeated many times, and each subsequent treatment is unfortunately less effective. The solvent condensate is recovered and its small amounts dissolved in the oil do not deteriorate the properties of the insulation system [19], [22], [23]. For many years, the method was considered the most effective but unfortunately, the solvent vapors in combination with air can ignite, which is a serious hazard. It is also a method that is difficult to apply in the field.

The last method of drying is based on heating the windings with a low frequency current in a vacuum environment. In this method, the paper insulation is heated by the flow of current in the windings. A voltage of adjustable frequency is applied to the HV winding and the LV winding is short-circuited. The frequency of the voltage is lowered to a value of about 0.5-1 Hz. At this frequency, the transformation effect still occurs, and the low and high voltage windings heat up to a similar temperature. In the initial stage of drying, the oil circulates between the transformer tank and the heating and drying unit. This way the transformer insulation cylinders made of pressboard heat up. In the next drying stage, the oil is drained and a vacuum of less than 1 mbar is created in the tank. To improve the drying efficiency it is also possible to use hot oil spraying on the insulation [15], [24]–[26]. The method is considered to be the best method used so far. The method allows drying the insulation to a level in the range from 0.5 to 1.5%.

B. JUSTIFICATION OF DEVELOPING A METHOD OF DRYING TRANSFORMER INSULATION ON-SITE

The methods listed in the previous chapter have some drawbacks and limitations, which have become an incentive to search for new solutions. In the case of the circulating hot oil drying method subjected to continuous vacuum drying, widely used many years ago, its low efficiency can be noted. For example, to reduce the moisture content of a 400 MVA transformer from 3% to 1.5% by using a heating system that provides an average temperature of the insulation system at 50 °C and by using an oil treatment system with a capacity of 6000 l / h, the drying procedure should be carried out for about four months [26].

On the other hand, methods using high vacuum, which is required to achieve the expected results, are troublesome because of the difficulty in ensuring the tightness of the tank and its insufficient mechanical strength, especially in the case of old transformers. In the case of medium-sized transformers (with a power in the range of 10-40 MVA), the permissible limit of negative pressure that can be applied to the tank is 0.5 bar, which makes it practically impossible to achieve moisture below 2%. Another problem associated with the use of reduced pressure is the partial de-impregnation of cellulosic materials, which may contribute to the deterioration of the dielectric parameters of the insulation. The consequence of de-impregnation of solid insulation may be local amplification of the electric field and lowering the ignition voltage of partial discharges.

In other methods, which do not require tank tightness, because the pressure gradient has been replaced by a temperature gradient, other problems arise in ensuring uniform heating of the insulation and proper temperature measurement. This is the case when the insulation is heated with hot air. In case of air overheating, ignition of oil vapors or local acceleration of insulation degradation may occur, which is unacceptable.

Other methods of the highest efficiency, i.e. the evaporation method and the LFH method, have the above-mentioned disadvantages, and additionally are very energy-consuming and pose a risk of damage to the dried unit, e.g. due to ignition of solvent vapors in the evaporation method or insulation breakdown in the LFH method, when the vapor pressure reaches the Paschen minimum and the high voltage is applied to the winding during this time. These methods, in the mobile version, also require the use of complex equipment, hence there are few such solutions in the world.

The above limitations and disadvantages can be eliminated in the method that is the subject of the research described in this article.

Dielectrics liquids such as mineral oil, silicone oil, natural ester, and synthetic ester have different water solubility. For example, at 50 °C, the water saturation limit in synthetic ester (2739 ppm) is about 18 times greater than in mineral oil (155 ppm) [27]. This property of synthetic ester can be used to efficiently drying cellulose insulation.

The procedures for drying cellulose insulation with synthetic ester may vary. Dry ester can be introduced into the tank once, which is quite simple but does not provide a satisfactory drying effect. In such a case, the drying efficiency strongly depends on the weight ratio of the insulating liquid to the cellulose insulation. This efficiency can be improved by introducing dry ester to the tank several times, which is troublesome for technical reasons because requires the transport of large amounts of dry ester. There is no economic justification for this approach. It is also possible to force the ester to circulate between the transformer and the ester vacuum drying unit, and this approach will have the highest efficiency.

III. EXPERIMENT

A. RESEARCH SETUP AND TEST OBJECT

The laboratory model of cellulose insulation drying must ensure the circulation of the ester as well as its heating and drying. Figure 2 shows a scheme of such a laboratory model. The test object was placed in a thermally insulated chamber (TIC). At the entrance to the chamber, a peristaltic pump (PP) with an adjustable flow rate was installed. At the outlet, a flow meter (FM) with a valve (CV) regulating the ester flow was placed. The liquid flow rate was controlled and matched to the efficiency of the drying unit (vacuum aggregate) that will be used in the future in a mobile system.

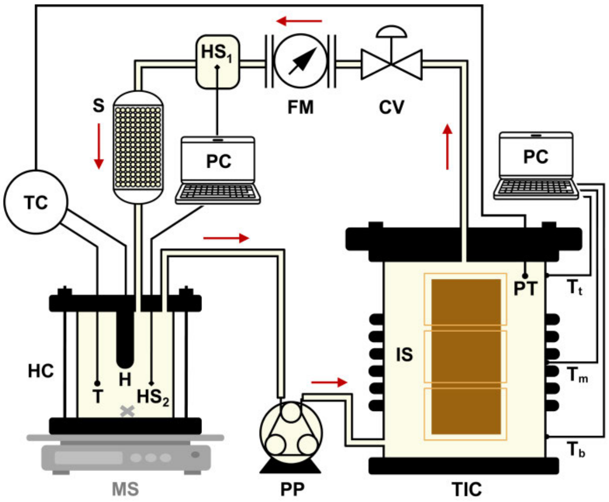

FIGURE 2. Laboratory model scheme used for drying insulation system; HC – heat chamber, TIC – thermally insulated chamber, TC – temperature controller, PT – resistance probe PT100, IS – insulation system (test object - model of transformer windings), T_t, T_m, T_b, T – thermocouples, CV – control valve, FM – flow meter, S – molecular sieves, HS$_1$ – humidity sensors measuring water content in ester entering molecular sieves (WCE1), HS$_2$ – humidity sensors measuring water content in ester exiting molecular sieves (WCE2), MS – magnetic stirrer, PP – peristaltic pump, PC – personal computer.

In real conditions, drying of the ester will be carried out with the use of a vacuum aggregate, while in the laboratory model, 3A molecular sieve was used. The weight of the sieve was selected so that the moisture of the ester pumped into the thermally insulated chamber with the insulation system (test object) did not exceed 130 ppm. At the entrance to the molecular sieve (S), a humidity sensor HS$_1$ was installed to measure temperature and ester moisture.

After leaving the molecular sieve, the ester is directed to a chamber (HC) with a power-regulated heater (H). The heater maintains the ester temperature at 85 °C, which corresponds to the capabilities of vacuum aggregates. The temperature and the moisture of ester in this chamber were measured using humidity sensor HS$_2$. Then the ester is pumped into the thermally insulated chamber with the test object.

The thermally insulated chamber, in which the model of the transformer windings was placed, was made of a flexible bellow. On the outer wall of the chamber, the temperature was measured in three places by means of thermocouples T_t, T_m, and T_b. Moreover, the ester temperature in the upper part of the chamber was measured with a resistance probe PT100.

The tested object was the model of the layer winding shown in Figure 3. The winding is made of profiled copper wire insulated with paper. The strips made of pressboard with a thickness of 2.2 mm were placed between the layers, forming oil channels. Samples for testing cellulose moisture before and after the drying process were cut out of these strips. The tested object, while maintaining an appropriate scale, had the construction of a typical cylindrical insulation system of a power transformer.

FIGURE 3. Test object (insulation system) – the model of the layer winding.

A photograph of the complete test system is shown in Figure 4.

FIGURE 4. Photo of the laboratory model of drying system.

B. RESULTS AND DISCUSSION

The synthetic ester Midel 7131 was used for drying. Table 1 shows the effect of temperature on the solubility of water in the ester as well as the viscosity and density of this liquid. These parameters are important due to the drying method used. The data presented in the table clearly show that high temperature is a factor improving the drying efficiency, with its growth, the water saturation limit in the ester increases, and the viscosity of this liquid decreases.

TABLE 1. The influence of temperature on chosen properties of synthetic ester.

Property	Temperature, °C						
	30	40	50	60	70	80	90
Water saturation limit, ppm [27]	2058	2385	2739	3120	3527	3959	4416
Viscosity, mm^2/s [28]	43	28	19.5	14	10.5	8	6.5
Density, kg/m^3 [28]	963	956	948	941	934	926	919

The initial water content in synthetic ester was equal to 120 ppm. Figure 5 shows the moisture content of the ester entering the molecular sieve (WCE1) and exiting the sieve and passing through the heater chamber (WCE2). The drying process lasted 7 days. After the first two days, the molecular sieve in the adsorber was replaced. After replacing the sieve, the moisture of the ester decreased rapidly. As drying time passed, the moisture of the ester entering and exiting the sieve increased slightly, but the efficiency of the molecular sieve was constant. The difference in the moisture content of the ester entering and exiting the sieve was constantly around 10 ppm. The moisture of ester exiting the sieve was maintained at a satisfactory level of 100-130 ppm.

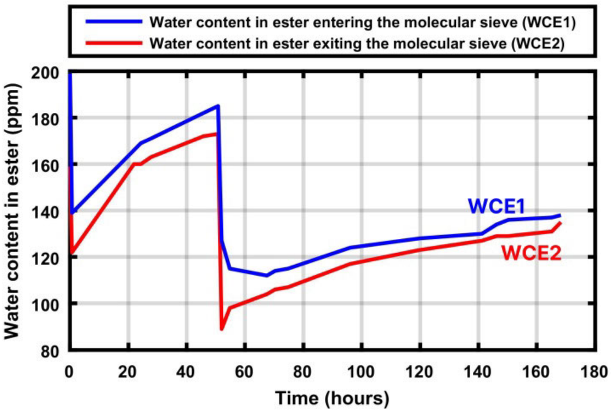

FIGURE 5. Water content in ester entering (WCE1) and exiting (WCE2) the molecular sieve.

After 168 h (7 days), i.e. after completion of the assumed drying process, the moisture content of cellulose samples taken from the pressboard strip was determined. Samples were taken from the top, middle, and bottom part of the strip. Moisture was determined using the Karl Fischer method. The results of cellulose drying expressed as percentage by weight are shown in Table 2.

As can be seen from the table, during the 7 days of drying the cellulose insulation, an average of about 1.08 percentage point of water was removed from the samples, with ester moisture remaining at the level of 100-130 ppm and with an average temperature of the insulation system of 70 °C.

TABLE 2. Results of drying samples; pressboard thickness 2.2 mm, ester moisture 100-130 ppm, ester temperature in the upper part of the winding model 74-78°C, drying time 168 h.

Place of taking samples from the strip	Water content in sample, wt%		Water loss in the sample after drying, p.p.
	Before drying	After drying	
Top	2.20	1.18	1.02
Middle	2.48	1.13	1.15
Bottom	2.40	1.33	1.07

The moisture equilibrium curve presented in Figure 6 shows that maintaining the moisture of the synthetic ester at the level of about 130 ppm should allow drying the pressboard even to the level of about 0.5%.

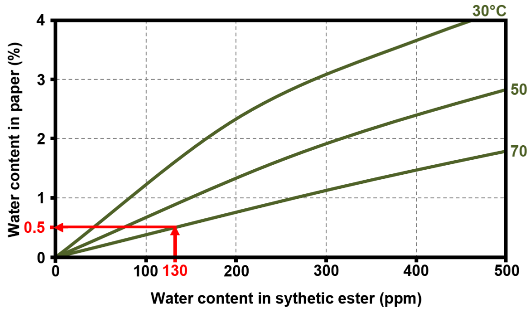

FIGURE 6. Moisture equilibrium curves for cellulose paper–synthetic ester system, based on [27].

To obtain such a low level of moisture, the drying time should be significantly extended due to the time needed for water migration inside the cellulose material. The drying result obtained in the experiment at the level of about 1.2% is satisfactory. A transformer with such a low level of moisture can be operated without restrictions, and the risk of its failure is significantly reduced.

Comparing the obtained results with the drying efficiency of transformer insulation with the use of different methods (Fig. 7), it seems that the method under development has great potential. Based on the conducted research, as well as previous analyzes presented, for example, in [15], it can be assumed that its efficiency will be very high and comparable to the effectiveness of the LFH method equipped with an oil spray installation. The procedure assumes drying for one week, which will allow the transformer to dry to the level of 1.5%, with appropriately selected procedure parameters and assuming the initial insulation moisture at the level of 3%. The effectiveness of the drying using circulating synthetic ester was estimated on the basis of the results of laboratory tests presented in [29]. In the presented comparison, only the evaporation method is a better method, however, the authors of the cited publication assumed that drying of this type can only be performed in the factory, using stationary equipment.

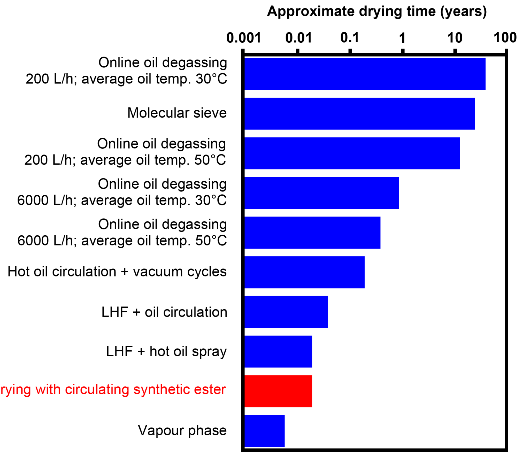

FIGURE 7. Drying time to dry a 400 MVA transformer with 14 ton insulation from 3% down to 1,5 % average humidity, based on [15], [29].

The effectiveness of the method presented in this article results mainly from the intensive and uniform heating of the insulation by means of synthetic ester and its high water solubility. In addition, it is worth noting that the method does not need to seal the tank, because in this case vacuum is not used, which will reduce the time needed to prepare the transformer for the drying procedure.

The undoubted advantage of reducing the moisture content of the insulation system is the improvement of safety and the extension of the transformer operation. As the water content in the insulation system decreases, its electrical strength increases and the cellulose depolymerization process slows down.

IV. RESULTS

Effective drying of the solid insulation of distribution transformers based on the use of a vacuum is often not feasible due to the insufficient compressive strength of the tank or due to insufficient tightness of the transformer. For this reason, the authors propose an alternative method that uses an electro-insulating liquid characterized by high water solubility in the drying process of cellulose insulation.

The described experiment concerned drying the transformer insulation system model using circulating synthetic ester. The initial moisture of the pressboard was about 2.3%, the water content in the ester using for cellulose drying was in the range of 100-130 ppm, and its temperature in the upper layer of the winding model was 74-78 °C. After 168 h, the water content decrease in the pressboard strips was 1.08 p.p.

Of course, the application of the method in the field requires further work on the procedure itself and the prototype of the system. For example, instead of a moisture absorber based on a molecular sieve, it is planned to use an aggregate heating and drying the ester in a vacuum, which will ensure similar efficiency of the drying process. The obtained test results constitute the basis for the validation of the method on distribution transformers.

The presented research results were obtained during the project Mobile system for drying insulation of distribution transformers with the use of a liquid medium. The project is financed by the National Center for Research and Development. As a result of the project implementation, a mobile insulation drying system for distribution transformers will be created.

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