

An Experimental Investigation on the Synthetic Ester Circulation for Drying Cellulose Insulation in Distribution Transformers

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ABSTRACT

Water can cause damage to power transformers by accelerating aging processes, reducing the dielectric margin, decreasing the partial-discharge inception voltage, and increasing the risk of unexpected failures. Modern electrical companies utilize a variety of drying techniques but sometimes do not comprehend them, making drying less effective. To address these challenges, this study proposes the application of synthetic ester to dry distribution transformers because water dissolves better in the ester than other dielectric liquids. An improved laboratory model of transformer insulation was used for the investigation. This model dried the ester using a molecular filter and carefully selected adsorbed weight. Pressboard strip water content before and after drying was analyzed to determine the drying efficacy of the cellulose insulation. The water content was measured using the Karl-Fischer titration method. The investigation proved that the drying procedure worked. At an ester moisture level of 105-120 ppm and an insulation system temperature of 70°C, samples dried for 5 days showed above 1% water loss. The experimental investigation demonstrated the high efficiency of the proposed drying method for distribution transformers.

Keywords-drying techniques; power transformers; moisture; synthetic ester

I. INTRODUCTION

Power transformers often experience failures due to the degradation of their insulation. Moisture is a significant factor in paper aging, as it is both a catalyst and a consequence of these processes [1-2]. Typically, doubling the water content of

a dielectric paper will decrease its lifespan. A transformer with 4% humidity will age in 10 years as much as a transformer with 2% moisture content will age in two decades [3-4]. Transformers typically have a lifespan of 30 to 50 years, mainly determined by the condition of the insulating system,

which naturally deteriorates over time. Temperature is a crucial factor that influences the rate of reactions in mineral oil. Increasing oil temperature accelerates aging processes [5-6]. After 30 years, the insulation of tightly sealed high-power grid transformers generally contains around 2% water, but distribution transformers with freely breathing conservators can have up to 3% water [7]. Transformers with membrane-sealed conservator preservation systems loaded with mineral oil undergo a yearly increase in cellulose insulation moisture ranging from 0.05% to 0.06%. However, transformers mounted with conservators, which provide air circulation, may see a 0.2% increase [8]. For a transformer operating for about 20 years, the insulation can be classified as wet according to the three stages defined in the IEEE 62-1995 standard [9]. This might reduce the load capacity and require drying out the insulation. As oil degrades, it experiences changes in viscosity, acidity, water content, and electrical properties. Aged cellulose insulation undergoes oxidation, hydrolysis, and thermolysis [10]. These responses are distinct, and factors such as temperature, oxygen levels, water presence, and catalysts can affect the reaction rate. Transformer insulation deteriorates due to moisture. Oxygen levels and the high temperature of the insulating system influence the rate of motion. Cellulose paper degrades much faster with 3% moisture compared to 1% [11]. Increased moisture levels could result from the aging process and water leakage from the outside to the insulation system, in addition to variations in relative humidity and periodic pressure fluctuations. The conventional structure of high- and medium-voltage distribution transformers allows air to enter the oil, posing a challenging problem to address. This remains true even if a humidifier previously dried the air [12].

Recent advances in drying technology for distribution transformers have significantly improved efficiency and effectiveness. Optimizing vacuum levels and oil circulation temperatures in traditional vacuum drying and hot oil circulation methods can reduce drying time by up to 30% while maintaining insulation integrity [13]. In [14], the superior moisture absorption capabilities of synthetic ester fluids compared to mineral oils were emphasized, enhancing the drying process and extending the transformer lifespan. In [15], an advanced online drying system was introduced, which used molecular sieves and dynamic adsorption techniques to allow continuous moisture removal without transformer downtime. In [16], innovative heating techniques were discussed, such as inductive heating and direct electrical heating of the windings, which provide uniform heating and are more energy-efficient and faster than conventional methods, significantly reducing drying time and energy consumption. Collectively, these advances represent a significant step forward in the maintenance and reliability of distribution transformers.

Drying can extend the life expectancy of the transformer insulation with increased moisture levels. Transformer dryers heat the insulation and create a vacuum by drawing air from the tank. Direct Current (DC), high-temperature oil, elevated air temperature, and load frequency control that passes through the windings can cause the insulation to heat up. Heating both windings with Low-Frequency Heating (LFH) in a vacuum is currently the most effective drying technique. However, there is a low demand for HV/MV distribution transformers. Tank

leaks and compression issues often arise due to inadequate vacuum maintenance [17-18]. In contrast, various insulation papers are used, such as cellulose, Kraft, Thermally Upgraded Kraft paper (TUK), etc. [19]. In [20], the possibility of using cellulose sheets instead of TUK paper was explored. Cellulose insulating materials incorporate aramid fiber, which offers exceptional strength and heat resistance up to 220°C. There is a possibility that the cellulose insulating paper may have better heat resistance than the TUK paper. However, it is essential to consider other important factors. This study covered various factors, such as mechanical characteristics, moisture content, electrical stability, aging by-products, and tensile strength. Cellulose-insulating paper has the potential to be an attractive alternative to TUK [21].

Cellulose insulation is made with layers of cellulose and aramid. It consists of 70% cellulose, 30% thermally enhanced Kraft pulp, and 30% meta-aramid fibers. As a result, three layers are compressed into a single layer. Cellulose and aramid fibers comprise the outermost layers, and the uppermost layer is composed of TUK. Using cellulose fibers for paper support is a common practice [22]. The aramid fibers serve to stabilize and enhance the cellulose fibers. This structure aims to strengthen the mechanical durability of the paper in case the cellulose weakens due to aging processes. Aramid materials demonstrate outstanding thermal performance during air testing, with a thermal class rating that can withstand temperatures up to 220°C. In addition, they are resistant to the negative impacts of aging and have outstanding electrical properties. It is important to note that aramid materials are significantly more expensive than cellulosic materials [23]. This study presents an experimental investigation of the cellulose paper drying process with synthetic ester, exploring the impact of temperature on selected characteristics of synthetic esters to study how thermal aging and ambient humidity affect cellulose insulation. The main contributions of this study are as follows:

- Presents a novel drying technology for power transformers used in the power distribution sector. Water accelerates aging processes, reduces dielectric margin, decreases partial-discharge inception voltage, and increases the risk of unexpected failures in power transformers.
- Proposes using synthetic ester for drying distribution transformers because water dissolves better in ester than in other dielectric liquids, enhancing the drying effectiveness.
- Tests the proposed drying method on an improved laboratory model of transformer insulation, employing a molecular filter and carefully selected adsorbed weight. The effectiveness was measured by comparing the water content of the pressboard strips before and after drying using the Karl-Fischer titration method.
- Explains an industrial testing process. The drying procedure was proven to be effective, with samples showing above 1% water loss after drying for 5 days at an ester moisture level of 105-120 ppm and an insulation system temperature of 70°C. The experimental investigation demonstrated the high efficiency of the proposed drying methodology for distribution transformers.

II. PROPOSED DRYING METHOD

Throughout the production and operation of the transformer, ensuring that the cellulose insulation is dried correctly is a critical issue that affects the transformer's performance. According to current standards, cellulosic materials should ideally have no more than 1% moisture after manufacturing. However, well-dried insulation contains even less water. Another issue is the transformer drying out while in operation. This event occurred when several transformers, most coming from Western Europe, turned thirty. When electric power grid operators noticed an increase in accidents resulting in explosions and fires, they took immediate steps to address the issue. Table I shows a detailed summary of the insulation system on a distribution transformer.

TABLE I. SUMMARY OF INSULATION SYSTEM REACTIONS TO ELECTRICAL AND THERMAL STRESSES IN POWER TRANSFORMERS [24-26]

Chemical and Physical Dynamics of Insulation Oil			
Attributes	Responses/ Actions	Temperature (°C)	Outcomes
Electrical stress	Arcing	700-1200	Gas composition: Methane, Carbon Oxide, Hydrogen. Environmental factors: Moisture. Electrical phenomena: Discharge Particles (Ions, Electrons).
	Partial discharge	700	Moisture, Acids, Traces of acetylene, Hydrogen.
Thermal stress	Oxidation	120-130	Contaminants and impurities: Acids Moisture, Aldehyde, Ketone. Fault indicators or components: Fault gases.
	Hydrolysis		Chemical components: Acids, Carbon dioxide. Physical property modifier: Reduces interfacial tension.
Reactions in Insulation Paper			
Attributes	Responses/ Actions	Temperature (°C)	Outcomes
Thermal stress	Hydrolysis	60-150	Organic compounds: Glucose, Formic acid, Levoglucosan. Inorganic compounds: Carbon oxide, Carbon dioxide.
	Pyrolysis	>120	Alcohols: Ethanol, Methanol. Organic compound: Levoglucosan.
	Oxidation	60-65	Aldehydes: Aldehyde. Carbon compounds: Carbon Oxide, Carboxylic Acid, Ketone, Furanic compound. Water content: Moisture.

III. THE RELATIONSHIP BETWEEN MOISTURE, OXYGEN, AND TEMPERATURE ON LIFESPAN

A simulation model was developed to investigate the impact of hot-spot temperature, moisture content, and oxygen concentration in the cellulose and TUK insulation papers. Figure 1 shows the lifetime of a transformer using cellulose paper and TUK sheets at hot-spot temperatures ranging from 50 to 160°C. Insulation paper typically has moisture levels ranging from 0.5 to 3%. It is important to remember that the temperature, moisture, and oxygen levels should remain constant throughout the lifetime. Simulations indicate that there is a correlation between low- to high-oxygen levels and the

presence of three-layered surfaces. Figure 1 shows that low oxygen levels have a life-extending effect, in contrast to the other two oxygen levels. As oxygen concentration increases, the disparity in lifetime is reduced. The lifespan of cellulose paper is double that of TUK paper, as seen in Figure 1(a,b).

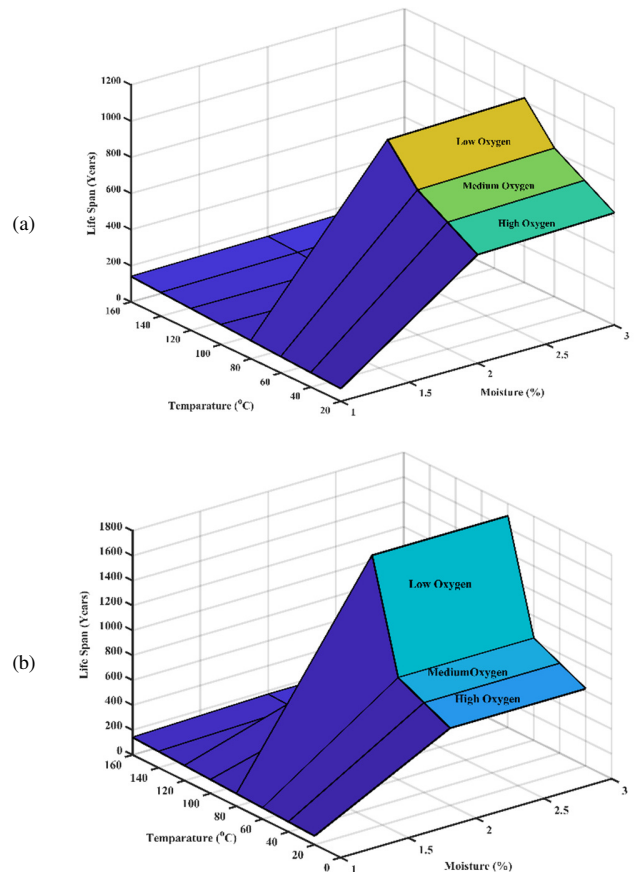


Fig. 1. Comparing the lifetime of three oxygen levels in terms of temperature and moisture: (a) TUK paper (b) cellulose paper.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the block diagram of the test model and Figure 3 shows the laboratory model to accurately produce and enhance the drying process of the cellulose insulation using ester solvents. Insulation system testing involves a detailed examination of the insulation used in electrical systems, particularly power transformers, to ensure its reliability and performance. This testing can be divided into two key components. The insulation system test subject, shown in Figure 3(a), refers to the actual insulation materials or components being evaluated, such as pressboard, paper, and dielectric fluids such as mineral oil or synthetic ester. These materials are evaluated to determine their ability to prevent electrical failures and withstand operational stresses. The laboratory testing system shown in Figure 3(b) encompasses the controlled environment and the specialized equipment used for these evaluations. This includes test apparatus that simulate real-world conditions, such as temperature and electrical stress, and measurement tools such as the Karl-Fischer titration for

moisture content and dielectric breakdown testers. The controlled laboratory setting ensures precise and reproducible conditions, allowing for an accurate assessment of the insulation's performance, aging, and degradation. Together, these elements provide comprehensive insights into the insulation's effectiveness, guiding maintenance practices and potential improvements in transformer design.

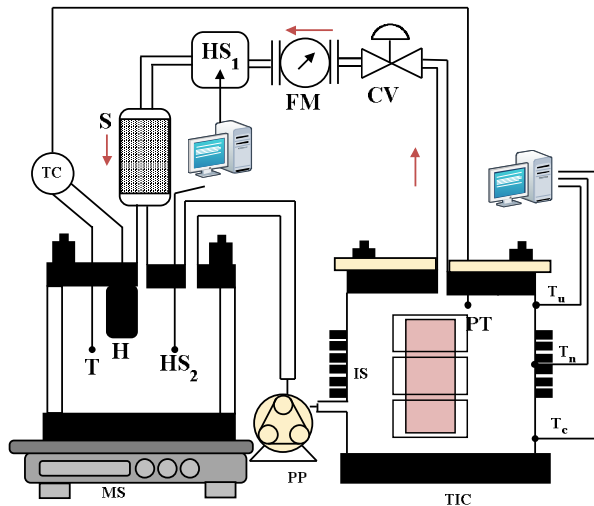


Fig. 2. Schematic of laboratory model for drying insulation system.

unload cycles, maintaining the winding under pressure for 2-3 minutes after reaching the force, as shown in Figure 4. Cellulose insulation is stored inside a container that is thermally insulated to regulate the drying process. By the chamber entrance, a Peristaltic Pump (PP) can circulate ester liquid throughout the system. Cellulose insulation promotes even heating and drying when circulated. A Flow Meter (FM) with a valve (CV) was fitted at the outlet to regulate the flow of the ester. Optimizing the liquid flow rate was crucial to align the performance of the vacuum aggregate drying unit with the desired efficiency, which would then be integrated into a portable system. In practical applications, the ester must dry using a vacuum system. However, in laboratory settings, a 3A molecular sieve was used for this purpose. The filter weight was adjusted to maintain the ester moisture content below 130 parts per million (ppm) in the thermally insulated container equipped with the insulation system (test item). The temperature and moisture content of the ester were monitored by employing a humidity sensor (HS1) placed at the entrance of the molecular sieve (S).

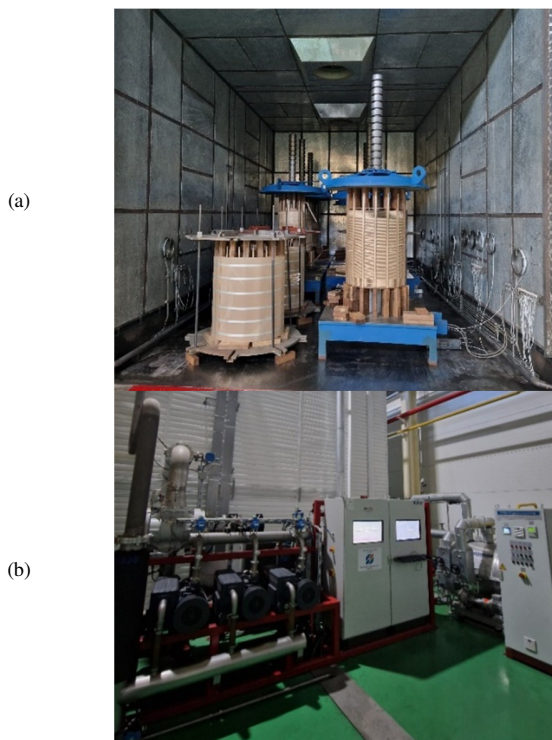


Fig. 3. Insulation system testing: (a) insulation system test subject, (b) laboratory testing system.

The first pressing of the winding is carried out with the force indicated in the drawing (1 cycle -100%) with three load-

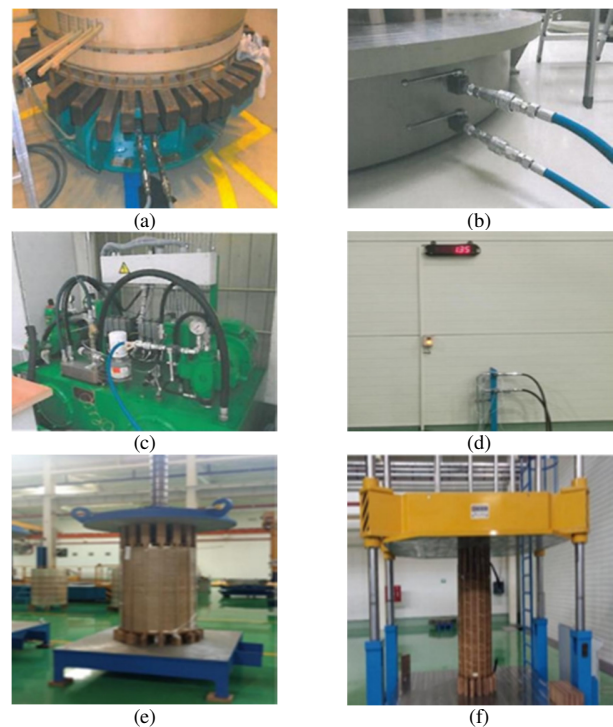


Fig. 4. (a)-(b) Connecting the hydraulic station to the stabilizing press, (c) Hydraulic unit for stabilizing press, (d) Connecting a stabilizing press to a vacuum drying cabinet, and (e)-(f) Installing the winding in a pressing device - Pressing the winding in a stabilizing press.

The HS2 humidity sensor is designed to detect the temperature and moisture levels of the environment. Then, the ester is placed into the chamber to protect the test item from high temperatures. Inside this chamber, there is a flexible bellow that encases the transformer winding model. A PT100 resistivity probe is used to measure the ester temperature at the top of the chamber. At the same time, thermocouples (Tu, Tn, and Tc) are used to track the temperature on the outer wall of

the chamber at three different points. An evaluation of the production of oil conduits between layers was carried out using a layer winding model consisting of a paper-insulated profiled copper wire and pressboard strips measuring 2.2 mm. Examining the moisture level of the cellulose involves checking the strips before and after the drying process. After thorough testing, the item accurately portrays a power transformer's cylindrical insulation system. This approach effectively tracks and quantifies the drying process of cellulose insulation in a controlled laboratory environment. This provides valuable insights into practical applications, such as the management of power transformer insulation.

A. Analyzing Temperature Influence on Key Attributes of Synthetic Esters

The drying procedure used the synthetic ester SYN-ESTER® 7131. Table II shows the impact of temperature on specific characteristics of the ester fluid, including viscosity, density, and solubility for temperature. The significance of these characteristics is ascribed to the selected drying technique. Enhancing drying efficiency at elevated temperatures necessitates the expansion of the water saturation threshold inside the ester and the reduction of the liquid's viscosity. The data shown in the table explicitly substantiate this assertion. The initial measurement of the water content in the synthesized ester was recorded at 120 ppm. The moisture levels of ester, shown in Figure 5, demonstrate its progression through the molecular sieve (WCE1), its subsequent exit from the sieve, and its subsequent movement through the heating chamber (WCE2). Impact of Temperature on Selected Characteristics of Synthetic Esters

Attributes	Temperature (°C)						
	35	45	55	65	75	85	95
Water Saturation limit (ppm)	3168	3474	3781	3899	3913	4122	4791
Viscosity (mm ² /s)	51	31	20.2	15	12.7	9.5	7.1
Density (Kg/m ³)	1015	976	955	945	934	928	921

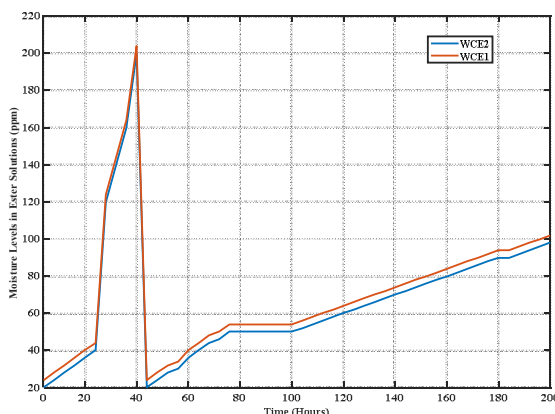


Fig. 5. The molecular sieve measures ester water content entering WCE1 and exiting WCE2.

The process of thorough drying took one week. A modification in the molecular sieve of the adsorber was observed after 48 hours. Following sieve replacement, there was a significant drop in moisture level. During the drying

process, the material that traversed the filter exhibited a modest increase in moisture content. The molecular sieve exhibited the expected performance. The moisture content of the ester exhibited a variation of around 10 ppm as it traversed the filter. The ester leaving the sieve was consistently kept within a moisture range of 100-130 ppm to maintain the desired moisture level. The estimated drying time was 168 hours (7 days). Subsequently, the moisture level of the cellulose samples from the pressboard strip was evaluated. Three specimens were collected from various sections of the strip. The Karl-Fischer method was used to assess the moisture content, and Table III shows the weight percentages of cellulose drying.

TABLE II. DRYING PROCESS FOR 168 HOURS USING A PRESSBOARD THICKNESS OF 2.2 MM

Optimal sampling points on the strip	Evaluation of moisture content in sample specimens		Quantifying water loss in dried samples
	Pre-drying water content in the sample	Post-drying water content in the sample	
Top	2.71	1.27	1.05
Middle	2.91	2.12	2.23
Bottom	2.84	2.41	1.97

B. Investigating Moisture Equilibrium Curves in Cellulose Paper

Figure 6 illustrates the moisture equilibrium curve, which suggests maintaining the synthetic ester's moisture content at 130 ppm while reducing the pressboard drying to 0.5%. Extending the drying process to facilitate the absorption of water through the cellulose decreases the moisture content. The experiment showed excellent results while using a drying method of 1.2%. When exposed to less moisture, a transformer can function with greater versatility and exhibit a lower probability of failure.

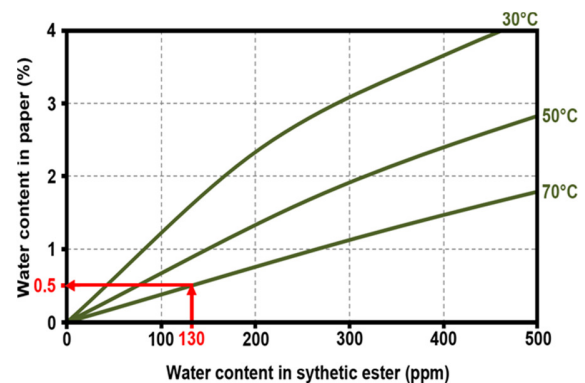


Fig. 6. Analysis of moisture equilibrium curves in cellulose paper - synthetic ester system.

C. Comparative Analysis

As shown in Figure 7, the proposed synthetic ester method is considerably promising compared to other techniques for drying transformer insulation. Research and analysis indicate that the method is very successful and is equivalent to the LFH technique with an oil spray installation. To achieve a transformer moisture level of 1.5%, a drying period of one week is expected. This assumption is based on carefully chosen experimental circumstances and a moisture content of 3%.

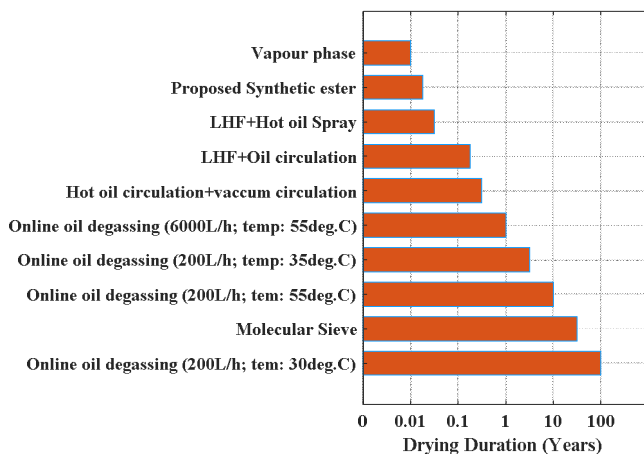


Fig. 7. Determining the required drying time for a transformer with 20-ton insulation.

In [26], the drying efficiency of a flowing synthetic ester was evaluated in laboratory investigations. The comparison indicates a preference for evaporation. However, this kind of drying could only be performed on a site equipped with permanent machinery. The efficacy of the proposed procedure is derived from the homogeneous and intense heating of the insulation using a water-soluble synthetic ester. There is no need to seal the tank. The time required to prepare the transformer for drying is reduced by omitting a vacuum. The reduction of the insulating moisture content can enhance the longevity and safety of transformers. As the water content of the insulation drops, an increase in electrical strength and a decrease in the rate of cellulose depolymerization are observed.

V. CONCLUSIONS

Vacuum drying of solid insulation in distribution transformers is impossible because of the tank's insufficient strength or inadequate transformer sealing. This study proposed an alternative approach that involves the application of a water-soluble electro-insulating liquid to the cellulose insulation during the drying process. An investigation was carried out on a prototype of a transformer insulation system that was subjected to a drying procedure using a circulating synthetic ester. Initially, the pressboard had a moisture level of 2.3%. The ester used to dry the cellulose had little water and usually ranged from 100 to 130 ppm. The temperature of the upper layer of the winding model fluctuated between 74 and 78°C. After 168 hours, the pressboard strips exhibited a reduction in water content of 1.08%. More efforts are required to ensure that the process and the system prototype are appropriate for implementation in real-life scenarios. A novel ester molecule was formulated as an alternative to conventional moisture absorbers that rely on molecular sieves to attain similar drying efficiency. This compound combines state-of-the-art heating and vacuum technologies. The test results validate the efficacy of the proposed method in distribution transformers.

Although the improved laboratory model showed high drying efficiency, there may be limitations when scaling the method for real-world applications. Laboratory conditions often differ from field conditions, and the effectiveness

observed in a controlled environment may not fully translate into operational transformers. Future research could focus on investigating ways to further optimize the drying process, such as refining the molecular filter and adsorbed weight parameters, to enhance efficiency. Additionally, the development of automated systems for continuous monitoring and drying of transformers could improve maintenance practices and reduce the risk of failure.

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