

Article

Diagnostics of High Water Content Paper-Oil Transformer Insulation Based on the Temperature and Frequency Dependencies of the Loss Tangent

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Abstract: The aim of the work was to prepare and test a paper-oil insulation system according to the recommendations of CIGRE (Conseil International des Grands Réseaux Électriques) with the parameters $X = 50\%$ and $Y = 30\%$. Pressboard was moistened to a water content of (5.0 ± 0.2) wt.%. The loss tangent was measured using a DIRANA meter (FDS-PDC dielectric response analyzer) in the frequency range 10^{-4} Hz–5000 Hz for 6 temperatures from 293.15 K to 333.15 K with a step of 8 K. The waveforms simulated by the DIRANA software were fitted to the experimental dependence of the loss tangent. The fitting process was performed using two methods. In the first method, the measuring temperature value as well as X and Y values were entered into the software. The estimated moisture content of the insulation varied from about 1.4 to about 5.2 wt.%. The average value of moisture content was (3.73 ± 1.11) wt.%. In the second method, only the measuring temperature value was entered into the software. This improved the quality of matching. The estimated average moisture content was (5.83 ± 0.25) wt.%. It was found that the dimensions of the oil channel clearly affected the quality of the fitting process. By not taking into consideration real values of oil channel, the quality of the moisture content estimation was significantly improved.

Keywords: power transformers; insulation system; dielectric materials; mineral oil; electrotechnical pressboard; insulation diagnostics; moisture; dielectric loss factor



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1. Introduction

The use of mineral oil in combination with cellulose as electrical insulation of power transformers dates back to the end of the 19th century [1–3]. The continued popularity of this type of insulation is due to its good electrical and mechanical properties as well as economic considerations. Cellulose, most often in the form of pressboard or paper, in combination with insulating oil, forms the so-called liquid-solid insulation. The role of the oil in this insulation system is to act as electrical insulation, work as a coolant, and protect the cellulose insulation against the ingress of moisture. The task of cellulose is to perform a structural and insulating function. In the transformer production process, after its assembly, the cellulose insulation is dried. Under vacuum conditions, the temperature of the insulation is raised in order to evaporate the water. Then, under reduced pressure, the insulation is poured over with heated and previously degassed insulating oil [4–6]. Cellulose has a capillary structure. In the process of oil pouring, the insulation is impregnated. Increased temperature of the insulating liquid facilitates impregnation of the insulation due to the inversely proportional dependence of the kinematic viscosity of the oil on the temperature. Then, the pressure in the transformer tank is equalized with the atmospheric pressure, which accelerates the impregnation process. The water content of new paper-oil insulation usually does not exceed 1 wt.%. Due to the negative impact of the potential

leakage of mineral oil into the environment, more and more emphasis is now placed on the use of more environmentally friendly insulating liquids. Natural and synthetic ester oils can be distinguished among the solutions currently used [7–9]. They are characterized by high biodegradability, electrical strength similar to or higher than that of mineral oil, and a high flash point. The disadvantage of ester oils is their high viscosity, which can significantly reduce the efficiency of the transformer cooling system. A new alternative to the previously mentioned insulating liquids is bio-carbon mineral oil. It is characterized by electrical parameters similar to classical mineral oil, but better in terms of thermal parameters, with high biodegradability at the same time [10–13]. The aforementioned parameters of bio-carbon oil result from its production process, which, unlike the refining of petroleum substances such as the case with mineral oil, uses a mixture of natural hydrocarbons. One example of such oils is NYTRO BIO 300X oil [13]. An alternative to cellulose is aramid paper, which is more resistant to temperature and moisture [14,15].

During many years of transformer operation, slow degradation of its insulation occurs. As aging processes progress, the electrical and mechanical properties of paper-oil insulation are reduced. The presence of water molecules in the insulation significantly accelerates the aging processes. The main source of moisture in the insulation is its penetration from the outside of the transformer. When the water molecules enter the tank, they dissolve in the oil which carries them to the cellulose. Due to over 1000 times higher solubility of water in cellulose than in oil, cellulose insulation accumulates moisture molecules [8]. When the moisture level of the transformer's paper-oil insulation exceeds 5 wt.%, it is necessary to turn it off [16,17]. There are methods for drying power transformers that reduce insulation moisture. The most popular method is the use of separators that dry the oil taken from the transformer, and then, return it to the tank. Due to the balance between the relative moisture content of the cellulose and the relative moisture content of oil, water migrates from the cellulose to the dry oil drying the insulation.

In order to prevent potential transformer failure, it is necessary to know its insulation moisture degree. Due to the fact that transformers are hermetic devices, it is not possible to take an insulation sample in order to perform chemical tests. For over 50 years, one of the most popular methods of assessing the moisture content of paper-oil insulation has been the use of Oommen curves to show the relationship between the moisture of mineral oil and the moisture of cellulose insulation [18]. In order to use this method, an oil sample is taken from the transformer, and then, it is analyzed for moisture by the Karl–Fischer titration method. Then, using the Oommen curves, the level of moisture in the transformer insulation is estimated. Unfortunately, this method has many practical limitations that significantly reduce its accuracy. Currently, nondestructive electrical methods are used to determine the condition of paper-oil insulation, with particular emphasis on the level of moisture. They can be divided into two groups. In the first group, DC voltage excitation is applied, and the dielectric response of the insulation system is recorded in the time domain. Examples of such methods are the polarization depolarization current (PDC) [19–21] and return voltage measurement (RVM) [22–24] methods. In the second group, a sinusoidal forcing voltage is used, allowing the response of the isolation system in the frequency domain to be observed, for example, the frequency domain spectroscopy (FDS) [25–27] method. Currently, the most frequently used method among the methods mentioned above is the FDS method [28–32]. Modern FDS meters, with the help of the software provided by the manufacturer, make it possible to estimate the moisture content of paper-oil insulation and the conductivity of insulating oil.

The latest research indicates the possibility of significant discrepancies between moisture content estimates using the software of FDS meters and actual insulation moisture [33]. The reason for the occurrence of such discrepancies may be the use of simplified models of conductivity and relaxation of oil-paper insulation.

Moistened, oil-impregnated insulating oil cellulose insulation forms a three-element composite, the conductivity of which depends on the water content. The research has proven that the electric current conduction in the composite takes place by tunneling

electrons between potential wells formed by water molecules [34]. In the works by [35,36], it was proven that water in paper-oil insulation occurred in the form of nanodrops with a diameter of about 2.2 nm, consisting of an average of 200 water molecules. The occurrence of quantum-mechanical electron tunneling between nearby nanodrops leads to the formation of temporary dipoles, causing additional polarization of the material. The lifetime of the dipoles formed in this way is determined by the dielectric relaxation time, which is the time from the moment of the electron tunneling to the nearby potential well, until its return to the potential well from which the electron was initially tunneling. The value of the dielectric relaxation time is influenced by the distance between the potential wells, the electric permittivity of the material, and the temperature [36].

Diagnostics of the transformer insulation condition is based on the measurements of the loss tangent [37,38]. Due to the geometric complexity of the insulation system, the CIGRE (Conseil International des Grands Réseaux Électriques) team of scientists proposed to use a simplified XY model of the insulation. In this model, the X parameter reflects the share of barriers, and the Y parameter reflects the share of spacers in the oil channel. The use of the XY model significantly simplifies the analysis of measurement results.

Research on the influence of the moisture content of paper-oil insulation on the value of the loss tangent has shown the presence of dipole relaxation in the ultralow frequency range as a result of electron tunneling between water nanodrops.

In the work by [39], an analysis of the temperature and frequency dependencies of $tg\delta(f)$ of a three-phase composite with a moisture content from 1 to 4 wt.% was performed. It was found that in the ultralow and low-frequency regions, dielectric relaxation of dipoles occurred as a result of electron tunneling between nanoparticles of water. The shapes of the $tg\delta(f)$ waveforms depend only on the moisture content, and their position in relation to double logarithmic coordinates is determined by temperature. Taking into consideration that the risk of transformer failure may occur after exceeding the critical moisture content of 5 wt.% [16,17], the pressboard with this moisture content had to be tested. Therefore, the aims of this study were:

- To prepare pressboard samples with moisture content of (5 ± 0.2) wt.% in a manner identical to the moisturization of insulation in power transformers and the construction of an XY insulation system, compliant with the CIGRE recommendations. The choice of the moisture content was chosen because exceeding this level may cause failure of the transformer.
- To perform measurements of the frequency and temperature dependencies of the loss tangent of the XY insulation system.
- To use the FDS meter software for fitting the simulated waveforms to the experimental dependence of the loss tangent of the XY insulation system.
- To estimate the moisture content of the cellulose component based on adjusting the system parameters, and to compare the obtained results with the actual parameters.

2. Materials and Methods

2.1. Preparation of the Insulation System According to CIGRE

The insulating system of power transformers, shown in Figure 1, includes barriers (1) and spacers (2) made of pressboard and oil ducts (3). This means that the insulation of the power transformer is a complex series-parallel cylindrical capacitor.

In publications [40,41], CIGRE proposed a simplified insulation system in the form of a series-parallel flat capacitor, as shown in Figure 2, to be used in the analysis of transformer insulation diagnostics results, using electrical methods. The capacitor contains a barrier of thickness X, which is the sum of the thicknesses of all the barriers in the transformer. The CIGRE model also has one Y-wide spacer and one oil channel.

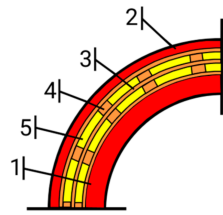


Figure 1. Scheme of windings and insulation of a power transformer. 1—low voltage winding; 2—high voltage winding; 3—barriers; 4—spacers; 5—oil channels [40,41].

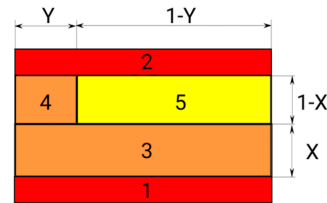


Figure 2. Electrical model of transformer insulation according to CIGRE. The heights of all components are the same and equal h . 1—low voltage winding; 2—high voltage winding; 3—barriers; 4—spacers; 5—oil channels.

The electrical model of the system shown in Figure 2 can be presented in two ways. The first system consists of an oil channel and spacers connected in parallel. A barrier is connected in series with them. The second system comprises a serially connected oil channel and a right part of barrier $1-Y$ wide. An element consisting of a spacer and the left part of the barrier with the width Y is connected in parallel to them. Due to the level of complexity, the second system is easier to calculate. It should be noted that the numerical results of the calculations according to both equivalent schemes should be the same. The CIGRE model assumes that the height of the windings is many times greater than the distance between the high and low voltage windings. The equivalent diagrams of both insulation electrical systems according to CIGRE are shown in Figure 3.

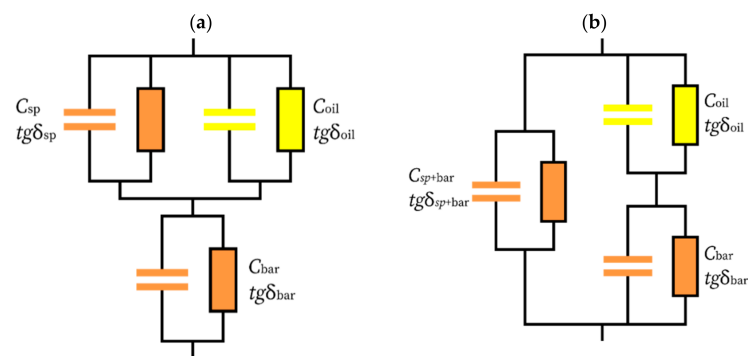


Figure 3. Electrical equivalent diagram of transformer insulation according to the CIGRE model: (a) parallel-series diagram; (b) series-parallel diagram. tg_{oil} , C_{oil} —loss tangent and capacitance of oil channel; tg_{sp+bar} , C_{sp+bar} —loss tangent and capacitance of spacers and left sided barriers; tg_{bar} , C_{bar} —loss tangent and capacitance of right sided barriers, tg_{sp} , C_{sp} —loss tangent and capacitance of spacers.

Each of the elements connected in parallel (capacitance and resistance) measured in a parallel equivalent diagram can be described with the respective values of the capacitance and the loss tangent.

In the case of a homogeneous insulation material, the value of the loss tangent is given by the formula:

$$tg\delta = \frac{\sigma}{\omega\epsilon\epsilon_0}, \quad (1)$$

where σ is the conductivity, ε is the permittivity, ε_0 is the vacuum permittivity, and ω is the angular frequency.

Formula (1) shows that in the case of a homogeneous material, the value of the loss tangent does not depend on the geometrical dimensions. For the transformer insulation system and the XY model (Figures 1–3), the loss tangent is a function of frequency, temperature, water content, and the X and Y parameters of the CIGRE model. In addition, it depends on the following electrical parameters: $t_{g_{cel}}$, pressboard loss tangent; $t_{g_{oil}}$, oil loss tangent; C_{oil} , oil channel capacitance; C_{sp+bar} , capacity of spacers + left side of the barriers; C_{bar} , capacity of the right part of the barriers. This means that the measurements of the transformer insulation loss tangent, performed by the frequency domain spectroscopy (FDS) method are a function of many variables. The DIRANA meter used for the research has the ability to adjust the simulated curves to the experimentally obtained loss tangent data. On the basis of the fitting, the program returns the following parameters of the insulation system: X and Y parameters, the conductivity of the insulating oil, and the insulation moisture content.

For the production of the XY insulation sample, 1 mm thick Weidman plates of pressboard were used, which were moistened in the same way as pressboard is moistened in power transformers during their many years of operation [32,42]. For this purpose, the pressboard plate was dried in a vacuum chamber. Drying was performed at the temperature of 80 °C for 72 h in a vacuum below 1 hPa. Then, leaving the plate in a vacuum, it was poured with mineral oil produced by Nynas, as is done in the production of transformers. The moisture content of the oil was several ppm. Then, two sources of moisture were prepared in the form of pressboard plates made using the traditional method [43–46]. It consists of drying the pressboard in a vacuum, then moistening it in the atmospheric air, and impregnating it with insulating oil. The sources of moisture are placed in a vessel with oil under and above the dried vacuum-impregnated plate. Supporters of 3 mm thick were placed between the dry and moistened plates to eliminate direct contact between them. The process of moistening the dried vacuum-impregnated plate is as follows: Water from the moisture sources diffuses into the oil. Mineral oil supplies moisture to the dry plate. The dry plate absorbs the moisture from the oil. A similar process takes place in power transformers. The humidification was performed at room temperature for over 18 months. The plates were moistened to a water content of (5.0 ± 0.2) wt.%. The water content selected is a limit value, and therefore, if exceeded, it could result in failure of the transformer [16,17].

An insulation system compliant with the CIGRE model was built with pressboard plates, as described above. The plates had the shape of circles with a diameter equal to that of the voltage electrode (Figure 4). Then, a hole was cut in one of the plates so that the cut part constituted 70% of the measuring electrode surface. After assembling the plates and placing them between the voltage and measuring electrodes, and pouring them with insulating oil, a system was created in accordance with the CIGRE model. Its parameters were: a barrier with a thickness of $X = 50\%$, a spacer with a width of $Y = 30\%$, and the remaining part, an oil channel (Figure 4). The volume of the oil channel was 35% of the total volume of the insulation system.

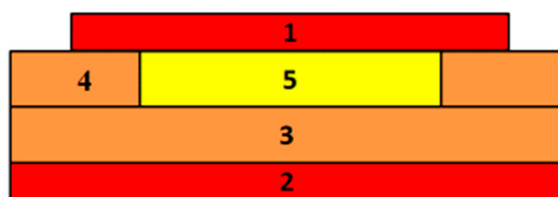


Figure 4. Cross-section of the XY system: 1—measuring electrode; 2—voltage electrode; 3—barrier with a thickness of 50%; 4—a spacer with a width of 30%; 5—oil channel.

2.2. Methods

The scheme of the measuring stand used to measure the loss tangent of the insulation system was described in the paper [47]. The insulating system located in a three-electrode capacitor was placed in a vessel flooded with insulating oil. After hermetic closure, the vessel was placed in the thermostat. The uncertainty of measuring and maintaining the temperature during the tests did not exceed ± 0.01 °C. A DIRANA meter (FDS-PDC dielectric response analyzer, OMICRON Energy Solutions GmbH, Berlin, Germany) was used for the measurements. In the frequency range from 10^{-3} Hz to 5000 Hz, 10 measurement points per decade were made, in the range from 10^{-4} Hz to 10^{-3} Hz, 6 measurement points per decade were made. Measurements were made at six temperatures from 293.15 K to 333.15 K in steps of 8 K.

Measurements were started at the temperature of 293.15 K. After it had stabilized, a capacitor was connected to the DIRANA meter and measurements were made at a frequency of 5000 Hz. Then, the frequency was gradually lowered and further measurements were made, after performing the measurement at the last frequency of 0.0001 Hz, measurements were made at the next temperature.

3. Research on the Insulation System According to CIGRE Parameters, Impregnated with Mineral Insulating

3.1. Research on the Frequency and Temperature Dependencies of the Loss Tangent of a Moistened Insulation System

Figure 5 shows the frequency dependence of the loss tangent of the insulation system according to CIGRE, consisting of a barrier and a spacer made of pressboard, impregnated with mineral oil. The pressboard was moistened to the water content of (5.0 ± 0.2) wt.%, in a manner identical to the humidification process in transformers. The channel was filled with mineral insulating oil.

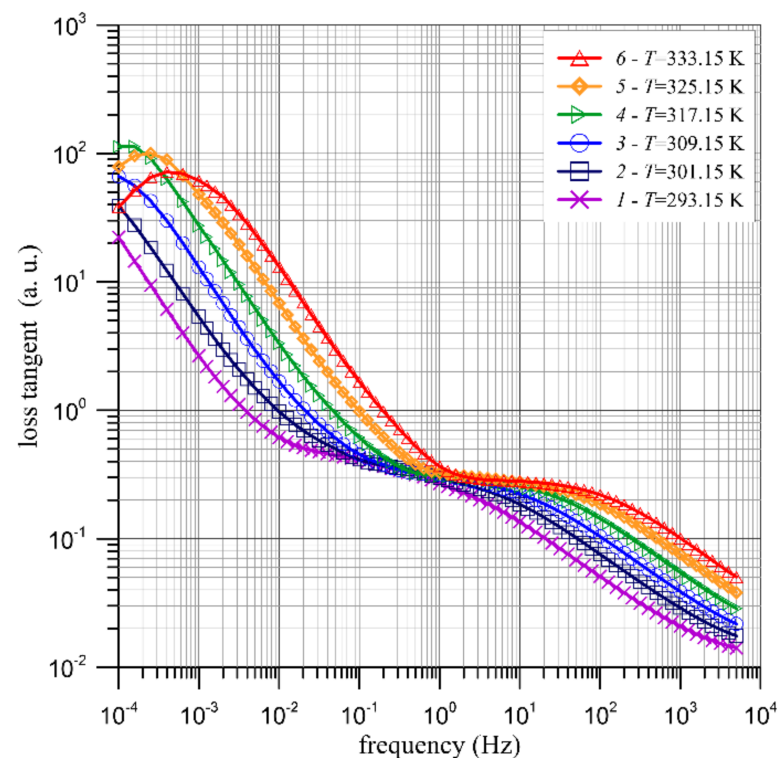


Figure 5. The frequency dependence of the loss tangent of the XY system consisting of the composite pressboard, insulating oil, water with moisture content of 5 wt.%, and insulating oil, for the measuring temperatures from 293.15 K to 333.15 K. Points—measurement results.

The measurements were made for six temperatures ranging from 293.15 K to 333.15 K. Figure 5 shows that temperature changes cause the waveforms to shift to a higher frequency region. The shapes of the waveforms practically do not change. A slight decrease in the value of $tg\delta$ in the waveform maximum is observed only in the frequency range below 0.001 Hz. In this frequency range, the course of the system loss tangent depends mainly on the mineral oil parameters [38,44,48]. The measurement results of the XY insulation system, shown in Figure 5, served as the basis for the analysis of insulation parameters using the DIRANA meter software. For this purpose, the software adjusts the simulated waveform to the waveform obtained from the insulation measurements. The software can determine the insulating oil conductivity value and estimate the moisture content. The software, in the absence of information about the geometrical dimensions of the transformer insulation, can also determine the X and Y parameters of the insulation system. Accordingly, the fitting process can be achieved following two methods. In the first method, the measuring temperature value and the X and Y parameters of the insulation are entered into the program, determined in accordance with the CIGRE model. The DIRANA meter software adjusts the simulated waveform to the experimental waveform and returns the conductivity values of the insulating oil and the pressboard water content given in wt.%. In the second method, only the measuring temperature value is entered into the program. The software completes the fitting process and returns the X and Y parameters, the oil conductivity value, and the pressboard water content. Such a situation may arise, for example, when testing older transformers, in which the geometrical dimensions of the insulation system are not known, which excludes the possibility of calculating the X and Y parameters.

3.2. Fitting the Loss Tangent Waveforms of a Moistened Insulation System and on This Basis Determining the Parameters of the Insulation Components, Known Values of X and Y

Figures 6 and 7 are examples of computer screenshots showing the experimental results and the fitting for the temperatures of 36 °C and 60 °C. Figure 6 shows a screenshot showing the experimental $tg\delta$ curve of the XY insulation system and the curve adjusted by the DIRANA meter software. On the left, there is a software control panel with parameters X = 50% and Y = 30%, and the measuring temperature of 36 °C. In the panel, the permittivity corresponding to the value for mineral oil of 2.2 was selected.

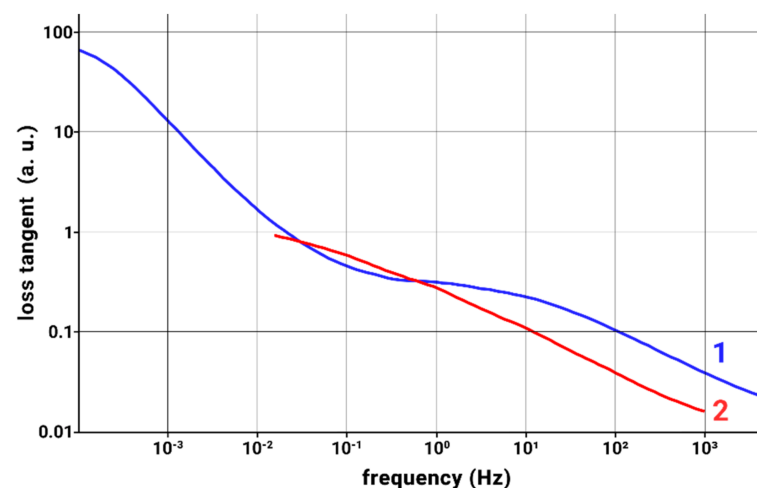


Figure 6. The experimental dependence of the loss tangent of the insulation system by X = 50% and Y = 30% measured at the temperature of 36 °C (1) and the curve fitted by the DIRANA meter software (2).

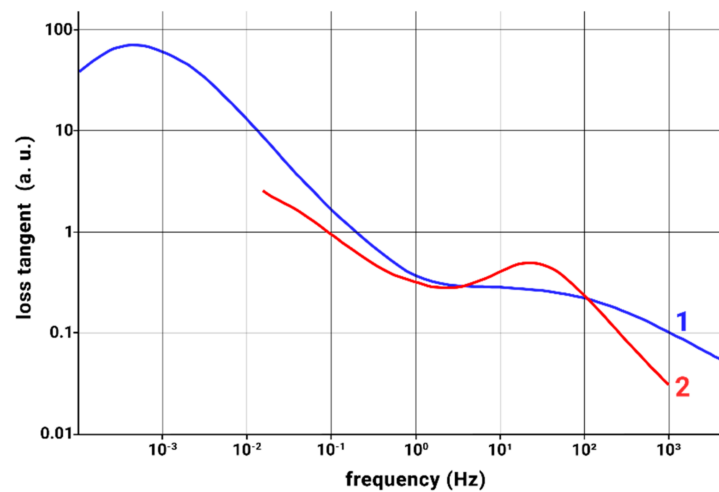


Figure 7. The experimental dependence of the loss tangent of the insulation system by $X = 50\%$ and $Y = 30\%$ measured at the temperature of $60\text{ }^{\circ}\text{C}$ (1) and the curve fitted by the DIRANA meter software (2).

Figure 6 shows that the fitted waveform is quite far from the measurement waveform. The parameters obtained on the basis of the fitting are oil conductivity at the temperature of $20\text{ }^{\circ}\text{C}$ amounting to $440.7 \times 10^{-18}\text{ S/m}$, oil conductivity at the measuring temperature of $1.0 \times 10^{-15}\text{ S/m}$, and moisture content of $5.2\text{ wt.}\%$.

Figure 7 shows similar results for the measuring temperature of $60\text{ }^{\circ}\text{C}$. In this case, the fitted waveform is also quite far from the measurement results.

In this case, the program provided the following parameters of the insulation system components: oil conductivity at $20\text{ }^{\circ}\text{C}$ of $1 \times 10^{-9}\text{ S/m}$, oil conductivity at $60\text{ }^{\circ}\text{C}$ of $7 \times 10^{-9}\text{ S/m}$, and moisture content of $1.4\text{ wt.}\%$. On the basis of the fittings made for all of the measuring temperature values, the temperature dependence of the moisture content in the mineral oil-impregnated pressboard was developed, as shown in Figure 8.

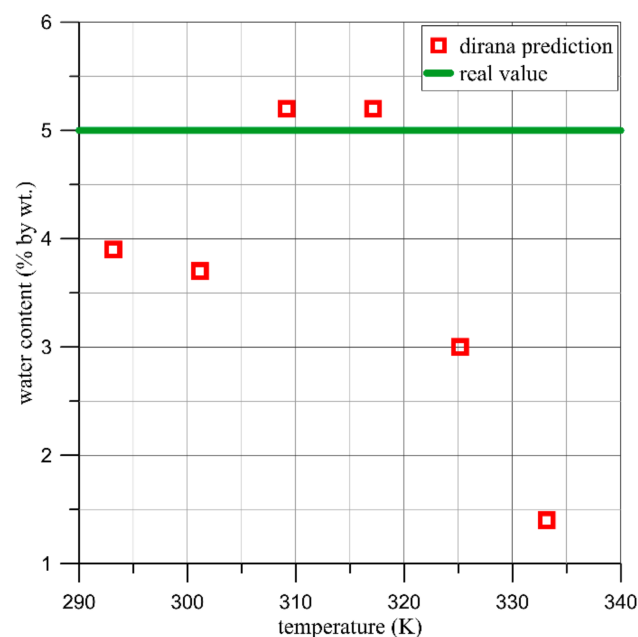


Figure 8. Temperature dependence of the moisture content, estimated on the basis of the software adjustment of the DIRANA meter with the input data of the X and Y values. Horizontal line—actual water content.

Figure 8 shows that the estimation of moisture content performed by the DIRANA software for different temperatures has very large spreads. The minimum moisture content value determined for a temperature of 60 °C was about 1.4 wt.%. Maximum moisture content values of about 5.2 wt.% were determined for the temperatures of 36 °C and 44 °C. The average moisture content value was (3.73 ± 1.11) wt.%. This means that the estimated value of moisture content by using the DIRANA meter is much below the actual value, which is (5.0 ± 0.2) wt.%. The difference between the actual value and the estimated average value is 1.27 wt.% or about 25%. In addition, there is a very high uncertainty in the estimation of the moisture content, amounting to ± 1.11 wt.% or $\pm 30\%$. These results are rather unsatisfactory.

Figure 9 shows the temperature dependence of the mineral oil conductivity, obtained by using the DIRANA meter software for the temperature of 20 °C. Figure 9 shows that during the fitting process of the waveforms for the system made according to CIGRE, the software introduces gigantic changes in the conductivity of the oil during the transition from one measuring temperature value to another. For example, when the temperature increases from 28 °C to 36 °C, a reduction in the conductivity of the oil by about six orders of magnitude is observed. With a further increase in temperature from 44 °C to 52 °C, there is a sharp increase in conductivity by more than six orders of magnitude. Such large changes in conductivity are rather impossible. For insulating materials, the conductivity should increase exponentially with increasing temperature.

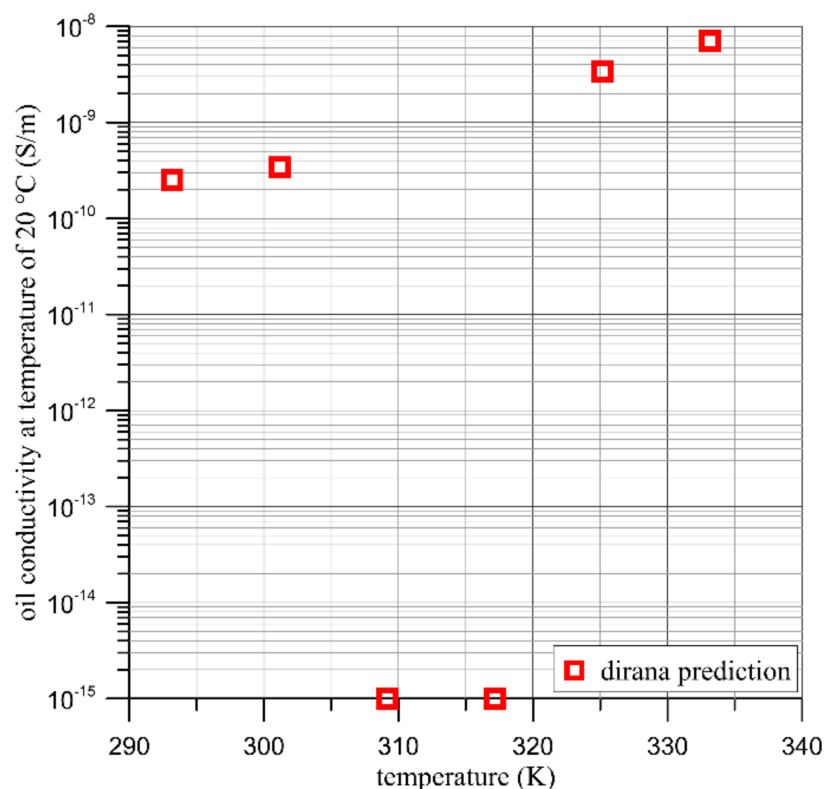


Figure 9. Temperature dependence of the oil conductivity at 20 °C, estimated on the basis of fitting by using the DIRANA meter software with the input data of the X and Y values.

3.3. Fitting the Loss Tangent Waveforms of a Moistened Insulation System and on This Basis Determining the Parameters of the Insulation Components, Unknown Values of X and Y

Figures 10 and 11 show, as an example, the experimental dependences of the loss tangent obtained at the temperatures of 36 °C and 60 °C. These are the temperatures for which the curves were presented in the previous Section 3.2. These figures also show the waveforms fitted by the DIRANA meter software. For this purpose, only the measuring temperature values were entered into the software. By comparing the waveforms presented

in Figures 6 and 10 for the temperature of 36 °C, it can be seen that performing the fitting without introducing the X and Y parameters to the DIRANA meter software significantly improved its quality. The best quality of matching occurs in the frequency range above 0.01 Hz. In this frequency range, the loss tangent of the insulation system depends mainly on the moisture content of the cellulose component [38,44,48]. After the fitting process, the DIRANA meter software returned an oil conductivity value of 1.1×10^{-12} S/m at 20 °C, water content of 5.9 wt.%, and the parameters of the CIGRE model $X = 92\%$ and $Y = 7\%$.

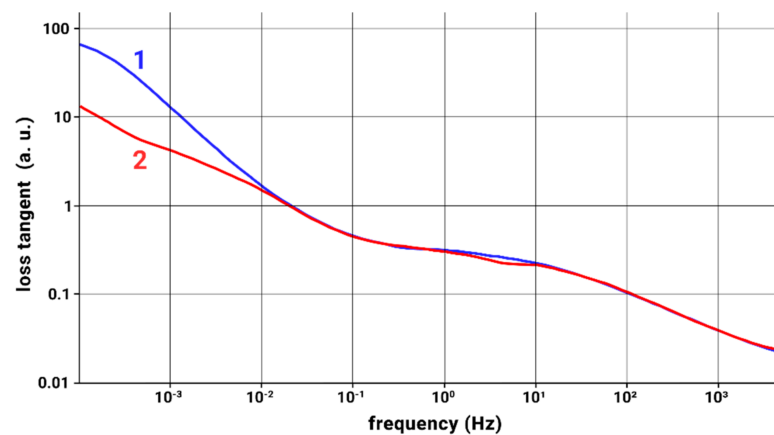


Figure 10. The experimental dependence of the loss tangent of the insulation system measured at the temperature of 36 °C (1) and the waveform fitted by the DIRANA meter software without introducing the values of X and Y (2).

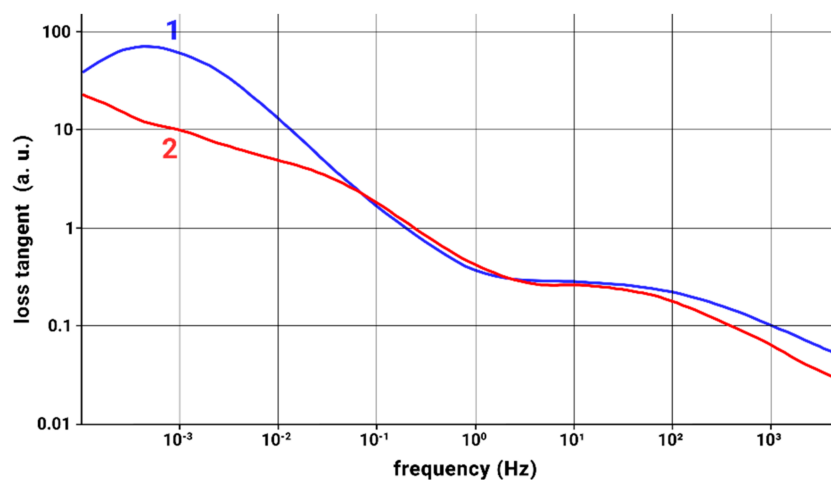


Figure 11. The experimental dependence of the loss tangent of the insulation system measured at the temperature of 60 °C (1) and the waveform fitted by the DIRANA meter software without introducing the values of X and Y (2).

Figure 11 shows the results of the fitting process without specifying the X and Y values for the experimental results, obtained at the measuring temperature of 60 °C. In this case, a good quality of matching was obtained at frequencies above 0.04 Hz. Similar results were obtained for the remaining measuring temperature values.

Based on the fittings made for six temperatures, the temperature dependence of the moisture content was determined, estimated by the DIRANA meter software, shown in Figure 12.

Figure 12 shows that the minimum value given by the DIRANA meter software, obtained at a temperature of 60 °C, is 5.3 wt.%, whereas the maximum value is 6.0 wt.% and the mean value $Z \approx (5.83 \pm 0.25)$ wt.%. It means that the estimated value of moisture

content is slightly overestimated in relation to the real value, amounting to (5.0 ± 0.2) wt.%, and the measurement uncertainty is close to the real one.

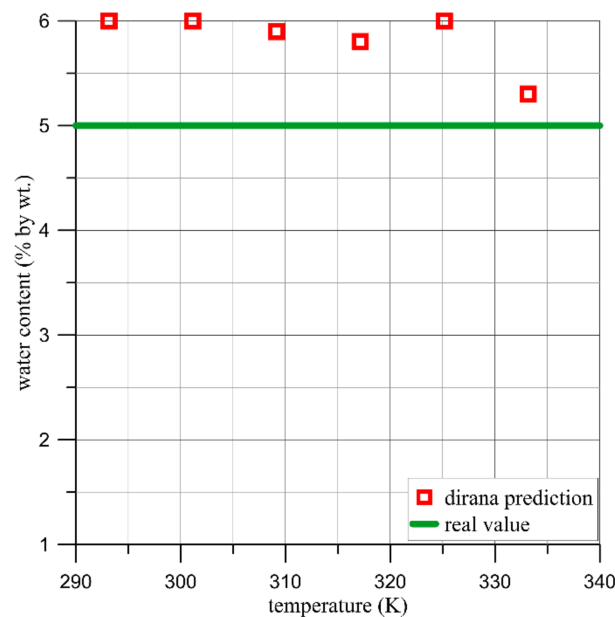


Figure 12. Temperature dependence of the moisture content, estimated by the DIRANA meter software fitting without entering the X and Y values. Horizontal line—actual water content.

Figure 13 shows the temperature dependence of the insulating oil conductivity, given on the basis of matching, converted to a temperature of 20 °C. As can be seen, with an increase in the measuring temperature value, the conductivity of the oil, converted to the temperature of 20 °C, increases from the value of about 6×10^{-13} S/m to about 4×10^{-12} S/m. This is possible due to the fact that as the temperature increases, the migration of moisture from the pressboard to the oil takes place. It results from the fact that the thermodynamic equilibrium between the moist pressboard and the oil shifts to the area of higher moisture content in the oil with the temperature increase [18].

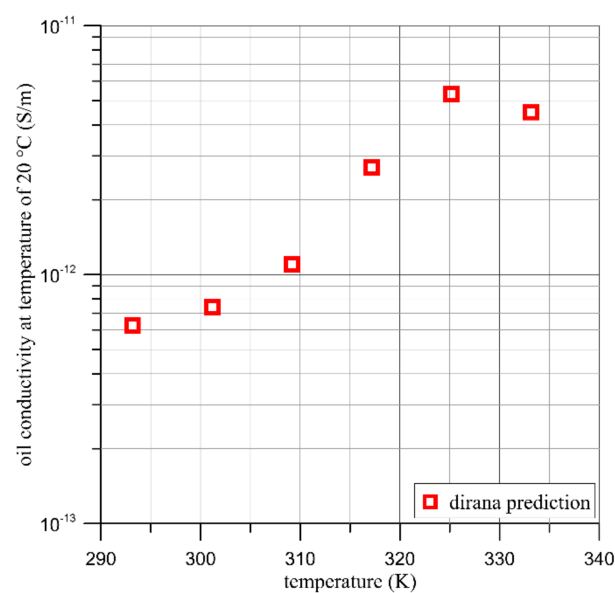


Figure 13. Temperature dependence of the oil conductivity at 20 °C, estimated on the basis of the fitting by the DIRANA meter software without the input of the X and Y values.

Figure 14 shows the temperature dependencies of the X and Y parameters, estimated by the DIRANA meter software. It shows that the values of the X parameter, estimated by the DIRANA meter, range from about 76% to about 92% and that the average value of the X parameter for all of the measuring temperature values is $83.3 \pm 6.80\%$. These values are approximately 1.66 times greater than the real value of 50%.

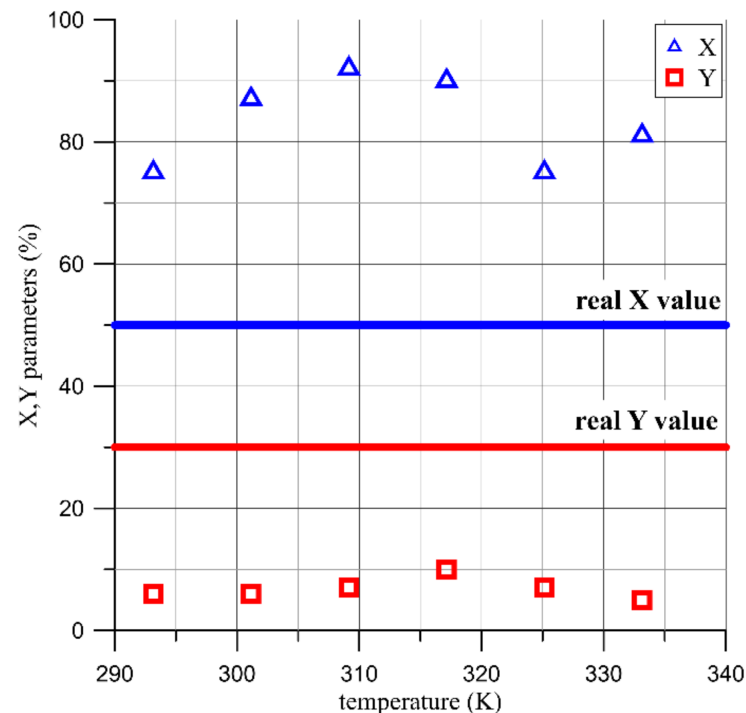


Figure 14. Temperature dependence of X and Y values, determined by the DIRANA meter software fitting. Horizontal lines—actual values of X and Y.

In the case of the Y parameter value, estimated by the meter for different temperatures, values range from about 5% to about 10%. The mean value is $Y \approx 6.85 \pm 1.57\%$, which is approximately 4.4 times less than the actual value of the insulation system of 30%.

On the one hand, when simulating without specifying the X and Y values, the moisture content is overestimated as compared with the actual value by about 17% with slight deviations from the average value. On the other hand, when entering the X and Y parameters, the estimated value of moisture content is underestimated by an average of about 25%, while the spreads for different temperatures are very large. In the examined model of cellulose-oil insulation, oil channels account for 35% of the total volume of insulation. The actual oil content in the insulation system is taken into consideration during fitting with known X and Y parameters. A simulation without specifying the values of X and Y, returning the model parameters, inflates the value of X and lowers the value of Y, thus, reducing the volume of oil to about 16%, i.e., to about 2.2 times smaller than the real volume. This improves the quality of the waveform matching and reduces the scattering of the moisture content estimation results. From the measurements and analysis of the XY CIGRE system, using the DIRANA software, it can be clearly stated that the introduction of the actual parameters of the oil channel significantly deteriorates the quality of the fitting and the accuracy of determining the moisture content. This is probably related to the difficulty of determining the exact parameters of insulating oil in real conditions, which is due to the fact that an increase in the temperature of the insulation system affects the conductivity of

the oil in two ways. First, there is an increase in conductivity, characteristic for insulating materials, described by an exponential relationship [49] as follows:

$$\sigma = \sigma_0 \exp\left(-\frac{\Delta W}{kT}\right), \quad (2)$$

where σ_0 is the numerical factor, ΔW is the activation energy, k is the Boltzman's constant, T is the temperature.

The second factor is striving, with increasing temperature, to achieve a thermodynamic equilibrium between the moisture content in the pressboard and oil, at a higher and higher level. The ratio of the moisture content of the oil and the pressboard is described by the Oommen curves [18]. They show that the moisture content in oil is several orders lower than in cellulose. Therefore, temperature changes practically do not change the moisture content of the cellulose component of the insulation system. An increase in temperature causes a significant increase in the moisture content of the oil through transition of moisture from the pressboard. The second factor also increases the conductivity of the oil and is much more difficult to describe analytically or numerically. This is due to the fact that the level of oil moisture after achieving the thermodynamic equilibrium depends both on the temperature and on the moisture content of the pressboard, which is unknown. These factors both cause the visible negative influences of the properties and dimensions of the oil channel on the results of the waveform matching, the insulation oil conductivity assessment, and the estimation of the moisture content in the solid component of the insulation system.

4. Conclusions

In this study, pressboard samples were used with a moisture content of 5 ± 0.2 wt.%, which had been moistened in a manner identical to the humidification of insulation in power transformers. The moisture content used in the work is a limit value, therefore, exceeding it could cause catastrophic failure of the transformer. An insulation system was prepared from the samples and mineral insulating oil, in accordance with the recommendations of CIGRE, with the parameters $X = 50\%$ and $Y = 30\%$. Electrotechnical pressboard produced by Weidmann and mineral insulating oil produced by Ninas were used to build the system; both of these insulation materials are dedicated to the production of insulation for power transformers.

The frequency and temperature dependencies of the of loss tangent of the XY insulation system in the frequency range from 10^{-4} Hz to 5000 Hz at temperatures from 293.15 K to 333.15 K were measured. The measurements were performed using a DIRANA meter (FDS-PDC dielectric response analyzer manufactured by OMICRON Energy Solutions GmbH, Berlin, Germany). The results of the measurements were used for fitting of the waveforms simulated by the DIRANA meter software to the waveforms obtained during the measurements. There were two methods for the fitting.

The first method involved entering the measuring temperature value and the actual values of X and Y into the software. The waveforms obtained with the fitting differed significantly from the experimental waveforms for all the measuring temperatures. The estimated values of moisture content of the cellulose insulation component varied irregularly from about 1.4 wt.% at 60 °C to a value of about 5.2 wt.% at temperatures of 36 °C and 44 °C. The average value of moisture content, determined for all the measuring temperature values was (3.73 ± 1.11) wt.% which was far from the actual value of (5.0 ± 0.2) wt.%.

An adjustment in the second method was made by entering only the measuring temperature value into the software. This significantly improved the quality of matching the simulated loss tangent waveforms to the experimental waveforms. The oil conductivity estimation results, converted to the temperature of 20 °C, look more reliable due to the occurrence of an almost monotonic increase in conductivity with increasing temperature. This is probably due to the moisture transfer from the pressboard to the oil. The estimated moisture content in this case also improves. The average value of moisture content, i.e.,

(5.83 ± 0.25) wt.% approached the actual value of (5.0 ± 0.2) wt.%, and there was a radical reduction in spreads.

It was found that the oil channel dimensions have a clear impact on the results of matching the simulated waveforms to the real waveforms of the frequency and temperature dependencies of the insulation system loss tangent. The transition from the actual channel dimensions (fitting in the first method) to the estimation without providing these values in the second method causes the DIRANA meter software to understate the estimated oil content in the system by about 2.2 times. There is an improvement in the quality of matching the simulated waveforms to the experimental loss tangent waveforms of the insulation system. This may mean, for example, that the meter software does not accurately reflect the temperature dependence of oil conductivity.

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References

1. Krause, C. Power transformer insulation—History, technology and design. *IEEE Trans. Dielectr. Electr. Insul.* **2012**, *19*, 1941–1947. [\[CrossRef\]](#)
2. Norris, E.T. High-voltage power-transformer insulation. *Proc. Inst. Electr. Eng.* **1963**, *110*, 428–440. [\[CrossRef\]](#)
3. Amoiralis, E.I.; Tsili, M.A.; Kladas, A.G. Transformer design and optimization: A literature survey. *IEEE Trans. Power Deliv.* **2009**, *24*, 1999–2024. [\[CrossRef\]](#)
4. Fabre, J.; Pichon, A. Deteriorating Processes and Products of Paper in Oil. Application to Transformers. In Proceedings of the International Conference on Large High Voltage Electric Systems, Paris, France, 15–25 June 1960. Paper 137.
5. Grackowski, A.; Gielniak, J. Influence of impregnating liquids on dielectric response of impregnated cellulose insulation. In Proceedings of the IEEE International Conference on Solid Dielectrics-ICSD, Potsdam, Germany, 4–9 July 2010; pp. 513–516.
6. Liu, J.; Zhang, H.; Geng, C.; Fan, X.; Zhang, Y. Aging Assessment Model of Transformer Insulation Based on Furfural Indicator under Different Oil/Pressboard Ratios and Oil Change. *IEEE Trans. Dielectr. Electr. Insul.* **2021**, *28*, 1061–1069. [\[CrossRef\]](#)
7. Rozga, P.; Beroual, A.; Przybylek, P.; Jaroszewski, M.; Strzelecki, K. A Review on Synthetic Ester Liquids for Transformer Applications. *Energies* **2020**, *13*, 6429. [\[CrossRef\]](#)
8. Lukenda, N. Not all mineral oils are equal—Exploring the history and technology behind mineral insulating oils. *Transform Mag.* **2019**, *6*, 112–117.
9. Mahanta, D.K.; Laskar, S. Electrical insulating liquid: A review. *J. Adv. Dielectr.* **2017**, *7*, 1730001. [\[CrossRef\]](#)
10. Fernández, I.; Ortiz, A.; Delgado, F.; Renedo, C.; Pérez, S. Comparative evaluation of alternative fluids for power transformers. *Electr. Power Syst. Res.* **2013**, *98*, 58–69. [\[CrossRef\]](#)
11. *MIDEL 7131 Increased Fire Safety*; M&I Materials Ltd.: Manchester, UK, 2016.
12. Liu, Q.; Wang, Z. Streamer characteristic and breakdown in synthetic and natural ester transformer liquids with pressboard interface under lightning impulse voltage. *IEEE Trans. Dielectr. Electr. Insul.* **2011**, *18*, 1908–1917. [\[CrossRef\]](#)
13. Wolmarans Carl, P.; René, A.; Bruce, P. Biodegradable electroinsulating fluids based on low viscosity hydrocarbons. *Energetyka* **2021**, *9*, 649–652.
14. Yin, F.; Tang, C.; Li, X.; Wang, X. Effect of Moisture on Mechanical Properties and Thermal Stability of Meta-Aramid Fiber Used in Insulating Paper. *Polymers* **2017**, *9*, 537. [\[CrossRef\]](#)
15. Tang, C.; Li, X.; Li, Z.; Tian, W.; Zhou, Q. Molecular Simulation on the Thermal Stability of Meta-Aramid Insulation Paper Fiber at Transformer Operating Temperature. *Polymers* **2018**, *10*, 1348. [\[CrossRef\]](#)
16. Hill, J.; Wang, Z.; Liu, Q.; Krause, C.; Wilson, G. Analysing the power transformer temperature limitation for avoidance of bubble formation. *High Volt.* **2019**, *4*, 210–216. [\[CrossRef\]](#)
17. Garcia, B.; Villarreal, R.; Garcia, D. A Multiphysical model to study moisture dynamics in transformers. *IEEE Trans. Power Deliv.* **2019**, *34*, 1365–1373. [\[CrossRef\]](#)
18. Oommen, T.V. Moisture equilibrium in paper-oil insulation systems. In Proceedings of the 1983 EIC 6th Electrical/Electrical Insulation Conference, Chicago, IL, USA, 3–6 October 1983; pp. 162–166. [\[CrossRef\]](#)

19. Sarkar, S.; Sharma, T.; Baral, A.; Chatterjee, B.; Dey, D.; Chakravorti, S. An expert system approach for transformer insulation diagnosis combining conventional diagnostic tests and PDC, RVM data. *IEEE Trans. Dielectr. Electr. Insul.* **2014**, *21*, 882–891. [\[CrossRef\]](#)
20. Zheng, H.; Liu, J.; Zhang, Y.; Ma, Y.; Shen, Y.; Zhen, X.; Chen, Z. Effectiveness Analysis and Temperature Effect Mechanism on Chemical and Electrical-Based Transformer Insulation Diagnostic Parameters Obtained from PDC Data. *Energies* **2018**, *11*, 146. [\[CrossRef\]](#)
21. Mishra, D.; Haque, N.; Baral, A.; Chakravorti, S. Assessment of interfacial charge accumulation in oil-paper interface in transformer insulation from polarization-depolarization current measurements. *IEEE Trans. Dielectr. Electr. Insul.* **2017**, *24*, 1665–1673. [\[CrossRef\]](#)
22. Martínez, M.; Pleite, J. Improvement of RVM test interpretation using a Debye equivalent circuit. *Energies* **2020**, *13*, 323. [\[CrossRef\]](#)
23. Islam, M.M.; Lee, G.; Hettiwatte, S.N. A review of condition monitoring techniques and diagnostic tests for lifetime estimation of power transformers. *Electr. Eng.* **2018**, *100*, 581–605. [\[CrossRef\]](#)
24. Fofana, I.; Hadjadj, Y. Electrical-Based Diagnostic Techniques for Assessing Insulation Condition in Aged Transformers. *Energies* **2016**, *9*, 679. [\[CrossRef\]](#)
25. Zhang, Y.; Liu, J.; Zheng, H.; Wang, K. Feasibility of a universal approach for temperature correction in frequency domain spectroscopy of transformer insulation. *IEEE Trans. Dielectr. Electr. Insul.* **2018**, *25*, 1766–1773. [\[CrossRef\]](#)
26. Liu, J.; Fan, X.; Zhang, Y.; Zhang, C.; Wang, Z. Aging evaluation and moisture prediction of oil-immersed cellulose insulation in field transformer using frequency domain spectroscopy and aging kinetics model. *Cellulose* **2020**, *27*, 7175–7189. [\[CrossRef\]](#)
27. Yang, L.; Chen, J.; Gao, J.; Zheng, H.; Li, Y. Accelerating frequency domain dielectric spectroscopy measurements on insulation of transformers through system identification. *IET Sci. Meas. Technol.* **2018**, *12*, 247–254. [\[CrossRef\]](#)
28. Zukowski, P.; Kierczyński, K.; Koltunowicz, T.N.; Rogalski, P.; Subocz, J.; Korenciak, D. AC conductivity measurements of liquid-solid insulation of power transformers with high water content. *Measurement* **2020**, *165*, 108194. [\[CrossRef\]](#)
29. Zukowski, P.; Rogalski, P.; Koltunowicz, T.N.; Kierczyński, K.; Subocz, J.; Zenker, M. Cellulose ester insulation of power transformers: Researching the influence of moisture on the phase shift angle and admittance. *Energies* **2020**, *13*, 5511. [\[CrossRef\]](#)
30. Zukowski, P.; Rogalski, P.; Koltunowicz, T.N.; Kierczyński, K.; Bondariev, V. Precise measurements of the temperature-frequency dependence of the conductivity of cellulose—Insulating oil—Water nanoparticles composite. *Energies* **2021**, *14*, 32. [\[CrossRef\]](#)
31. Zukowski, P.; Rogalski, P.; Kierczyński, K.; Koltunowicz, T.N. Precise Measurements of the Temperature Influence on the Complex Permittivity of Power Transformers Moistened Paper-Oil Insulation. *Energies* **2021**, *14*, 5802. [\[CrossRef\]](#)
32. Zukowski, P.; Rogalski, P.; Koltunowicz, T.N.; Kierczyński, K.; Subocz, J.; Sebok, M. Influence of temperature on phase shift angle and admittance of moistened composite of cellulose and insulating oil. *Measurement* **2021**, *185*, 110041. [\[CrossRef\]](#)
33. Zhang, M.; Liu, J.; Lv, J.; Chen, Q.; Qi, P.; Sun, Y.; Jia, H.; Chen, X. Improved method for measuring moisture content of mineral-oil-impregnated cellulose pressboard based on dielectric response. *Cellulose* **2018**, *25*, 5611–5622. [\[CrossRef\]](#)
34. Żukowski, P.; Koltunowicz, T.N.; Kierczyński, K.; Subocz, J.; Szrot, M.; Gutten, M. Assessment of water content in an impregnated pressboard based on DC conductivity measurements. Theoretical assumptions. *IEEE Trans. Dielectr. Electr. Insul.* **2014**, *21*, 1268–1275. [\[CrossRef\]](#)
35. Żukowski, P.; Koltunowicz, T.N.; Kierczyński, K.; Subocz, J.; Szrot, M. Formation of water nanodrops in cellulose impregnated with insulating oil. *Cellulose* **2015**, *22*, 861–866. [\[CrossRef\]](#)
36. Żukowski, P.; Kierczyński, K.; Koltunowicz, T.N.; Rogalski, P.; Subocz, J. Application of elements of quantum mechanics in analysing AC conductivity and determining the dimensions of water nanodrops in the composite of cellulose and mineral oil. *Cellulose* **2019**, *26*, 2969–2985. [\[CrossRef\]](#)
37. Kunicki, M. Experience in exploitation and diagnostics of high voltage transformers fleet. In Proceedings of the 2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Bari, Italy, 7–10 September 2021; pp. 1–5. [\[CrossRef\]](#)
38. Brncal, P.; Gutten, M. Diagnostics of Insulating Condition of Traction Transformer by Frequency Method. *Transp. Res. Procedia* **2021**, *55*, 977–982. [\[CrossRef\]](#)
39. Żukowski, P.; Koltunowicz, T.N.; Kierczyński, K.; Rogalski, P.; Subocz, J.; Szrot, M.; Gutten, M.; Sebok, M. Dielectric losses in the composite cellulose-mineral oil-water nanoparticles: Theoretical assumptions. *Cellulose* **2016**, *23*, 1609–1616. [\[CrossRef\]](#)
40. Fofana, I.; Zié, Y.; Farzaneh, M. Dielectric Response methods for diagnostics of Power equipment. *Recent Adv. Dielectr. Mater.* **2002**, *33*, 249–299.
41. Gubanski, S.; Blennow, J.; Holmgren, B.; Koch, M.; Kuechler, A.; Kutzner, R.; Lapworth, J.; Linhjell, D.; Tenbohlen, S.; Werelius, P. *Dielectric Response Diagnoses for Transformer Windings*; CIGRE: Paris, France, 2010.
42. Rogalski, P.; Kierczyński, K.; Żukowski, P. Method of Moistening an Electrotechnical Pressboard Impregnated with Insulating Oil. Polish Patent No. B1 239240, 15 November 2021.
43. Setayeshmehr, A.; Fofana, I.; Eichler, C.; Akbari, A.; Borsi, H.; Gockenbach, E. Dielectric spectroscopic measurements on transformer oil-paper insulation under controlled laboratory conditions. *IEEE Trans. Dielectr. Electr. Insul.* **2008**, *15*, 1100–1111. [\[CrossRef\]](#)
44. Koch, M.; Prevost, T. Analysis of dielectric response measurements for condition assessment of oil-paper transformer insulation. *IEEE Trans. Dielectr. Electr. Insul.* **2012**, *19*, 1908–1915. [\[CrossRef\]](#)

45. Ekanayake, C.; Gubanski, S.M.; Grackowski, A.; Walczak, K. Frequency Response of Oil Impregnated Pressboard and Paper Samples for Estimating Moisture in Transformer Insulation. *IEEE Trans. Power Deliv.* **2006**, *21*, 1309–1317. [[CrossRef](#)]
46. Samarasinghe, W.M.S.C.; Kumara, J.R.S.S.; Fernando, M.A.R.M.; Gunawardena, A.U.A.W. Aging assesment of transformer pressboard insulation by micro-strip ring resonator at GHz frequencies. *IEEE Trans. Dielectr. Electr. Insul.* **2017**, *24*, 1923–1930. [[CrossRef](#)]
47. Rogalski, P. Measurement Stand, Method and Results of Composite Electrotechnical Pressboard-Mineral Oil Electrical Measurements. *Devices Methods Meas.* **2020**, *11*, 187–195. [[CrossRef](#)]
48. Bigdeli, M.; Aghajanloo, J.; Azizian, D. Estimation of Moisture in Transformer Insulation Using Dielectric Frequency Response Analysis by Heuristic Algorithms. *Model. Simul. Electr. Electron. Eng.* **2021**, *1*, 27–35. [[CrossRef](#)]
49. Jonscher, A.K. *Dielectric Relaxation in Solids*; Chelsea Dielectrics Press: London, UK, 1983.