PATTERNS OF MOISTURE CONTENT IN INSULATION OF PAPER AND SYNTHETIC ESTER MIDEL 7131 USING THE FDS TECHNIQUE

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Abstract: The moisture content in paper-oil insulation is determined by using indirect methods based on the analysis of the dielectric response in the time and frequency domain. The evaluation procedure of moisture content in oil-paper insulation requires patterns. The patterns are created mostly on the basis of real and imaginary parts of complex permittivity in the frequency range from 0.1 mHz to 1 kHz. Several research centres in Europe have patterns of water content in paper-mineral oil. Up to now, the patterns of water content in paper-synthetic ester have not been published yet. The article presents some selected patterns of water content in paper-MIDEL 7131, as well as a comparison of patterns characterizing the paper impregnated by mineral oil and MIDEL 7131.

1 INTRODUCTION

The moisture of paper-oil insulation in power transformers is a very serious operational problem. There are three main reasons of insulation moisture, namely incomplete drying of the insulation during the technological process, generating water as a chemical decomposition product of cellulose as a result of ageing effects, and migration of moistened air into the tank through any leakinesses. Figure 1 presents, approximately, the dynamics of insulation moisture changes [1].

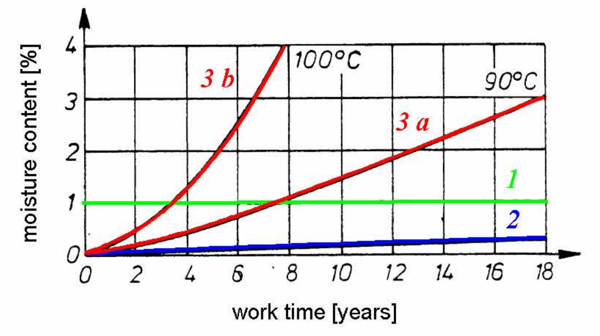

Figure 1: Increase of the moisture content in transformer insulation during operation, 1 – the moisture remaining after the production process, 2 – water diffusing through leakinesses, 3 – water coming from cellulose decomposition at 90^{o}C (a) and 100^{o}C (b) [1]

The most dangerous effect is water generation in the process of cellulose chemical decomposition. It was found that the water present in the insulation accelerates ageing processes [2]. The older the unit the greater annual moisture increase should be expected.

The water present in paper-oil insulation can be a reason of dangerous breakdowns. A phenomenon known as the bubble effect is one of consequences. This effect consists in violent emitting of water steam after exceeding a critical moisture and a critical temperature. There is a pressure increase in the tank to a level which causes an explosion, which in turn can lead to a fire [3, 4].

The problem of insulation moisture increases with passing years of transformer operation. Thus we can understand increasing interest in diagnostics of the insulating system state by transformer owners, particularly including reliable methods of determining paper-oil insulation moisture.

The choice of the method to determine moisture of cellulose insulation impregnated with oil depends on a type of the object. In the case of small samples used in the laboratory, a reliable titration method of Karl-Fisher is applied. If we prepare samples for laboratory needs and we require a certain moisture value, then we can make use of a simple reliable method which consists in vacuum drying of a sample to a level close to 0% of water, and next controlled moistening through a contact of the sample with humid air. During the moistening, the sample rests on precise scales, and as a result, controlling the sample mass, we can obtain a required moisture of the sample with high accuracy.

The problem is completely different when we have to determine moisture of the main insulation in the transformer. We assume that it is impossible to take a sample of paper or pressboard. Even if there was such a possibility during an operational checkup, the sample taken from the most easily accessible place would not be representative. We have to realize that there is distribution of insulation moisture along the transformer column and along the radius. The moisture of external layers differs from the moisture of internal layers, so that only in exceptional situations, when we have an opportunity to take cellulose samples from many places we can expect good information about the moisture of the whole insulation system of the transformer [5].

In reference to the insulation of a real transformer, the most useful are indirect methods. Among indirect methods, the most important are the ones based on the dielectric response. The dielectric response is meant as the response of a dielectric to the exposure to electric field. We can do the analysis of the dielectric response in the time domain or in the frequency domain. One of the most often applied methods of the frequency response analysis is FDS (Frequency Dielectric Spectroscopy). In this method, changes of electric permittivity and the loss factor are analysed in a wide frequency range, from 10^{-4} to 10^{3}Hz. The water present in the insulation causes very high shifts of characteristics in the range of infralow field frequencies. Two specifically going characteristics of the dielectric response (electric permittivity and the dielectric loss factor) correspond to arbitrarily chosen, exactly determined water content in the cellulose-oil insulation. Such characteristics are moisture patterns. The patterns are made for selected moisture levels from about 0.5 to 5% and for many temperature values, predominantly from 20 to 80^{o}C. A good pattern database should contain a few hundred characteristics.

While determining transformer insulation moisture, we make use of the patterns and at the same time include geometrical dimensions of the main insulation and the quality of insulating oil. The technique consists in matching pattern characteristics to the characteristics taken from an investigated transformer. The wider the pattern database the greater the accuracy of determined moisture.

A wide pattern database of paper - mineral oil insulation moisture was made as a result of an international research project REDIATOOL [6]. It was a common effort of three teams, from Poland, Sweden, and Germany to complete the database. Making use of specialistic equipment and the pattern database, we have determined insulation moisture of about one hundred power transformers up to now.

2 THE NEED TO CREATE MOISTURE PATTERNS OF PAPER – SYNTHETIC ESTER INSULATION

Recently, more and more transformers filled with synthetic oil are ordered in transformer factories. Insulating liquids, in the form of synthetic esters, have been known for quite a long time, but their high price discouraged from use at first. Good electroinsulating properties of esters, their non-flammability, inexplosiveness, bio-degradability, and recently their falling price, whereas prices of mineral oils have been rising lately; all these factors have caused that this type of insulation has been more interesting for both transformer factories and professional electric power engineering companies.

Medium-size distribution transformers, filled with synthetic esters are an ideal solution for big urban complexes, multi-storey buildings, hospital complexes, mining, and chemical industry.

A transformer company ABB in Poland, manufactures transformers filled with synthetic ester whose commercial name is MIDEL 7131. It is non-toxic. The liquid is non-toxic, also the smoke does not contain any toxic substances either. According to the harmonizing document HD 637 31, the ester is classified as safe for water, therefore, devices filled with it can be installed without the leakage protection system. So far, the effect of fish poisoning and ecosystem degradation has not been proved. Because MIDEL 7131 is not toxic, it is ideal for devices using sustainable power, mainly sea power (marine turbines, wave power), and wind power (most wind power plants are located at the seacoast).

Another important property, that ecologists are sensitive to, is biodegradability. Biodegradability, determined conventionally after 28 days is 89% for MIDEL 7131, whereas it is 9% for mineral oil and 0% for silicon oil.

Ester MIDEL 7131, thanks to its good flammable properties, is a minor threat for the environment and public safety. The ignition temperature of the ester, according to the ISO 2592 standard, is 317^{o}C, whereas for the mineral oil it is 170^{o}C. Due to its fire safety, MIDEL 7131 has been classified to class K. The ester of the temperature of 230^{o}C does not ignite when exposed to open fire, whereas in the same experiment, the mineral oil burns at the temperature of 80^{o}C. If there is a serious breakdown, even if the sprayed ester ignites, the fire is self-extinguished (according to IEC 60695-1-40 7.1). For devices filled with synthetic esters, installed at places of increased fire safety (eg. housing buildings), we can apply less strict conditions and lower requirements concerning safety equipment, which makes an investment substantially cheaper [7].

The Institute of Power Engineering of Poznan University of Technology has been cooperating with the ABB transformer company in Poland for many years. Lately the factory has been making transformers filled with synthetic ester, according to an order of investors from Western Europe. Design changes of the transformers and qualitative changes of the insulating system require evaluation of transformer drying efficiency. We were asked to determine insulation moisture after drying, but it turned that there was a problem, i.e. lack of moisture patterns of paper-synthetic ester MIDEL7131 insulation. In such a situation, we decided to make a database of moisture patterns for this kind of insulation. Taking this into consideration, we worked out a project which was granted financing and is still in progress [8].

3 EXPERIMENT

3.1 Research objects

The research objects are pressboard samples, 1.5 mm thick and of the diameter 160 mm. Sample preparation is an important stage. The samples are vacuum-dried at the pressure of 100 Pa, at the temperature of 100^{o}C and for 8 hours. Next the samples were placed on accurate scales and moistened to a demanded level through the contact with surrounding air. Sample moisture is determined on the basis of their mass changes. At the next stage the samples are closed in airtight chambers and impregnated with new dry ester MIDEL 7131. After impregnation the samples undergo conditioning in a thermal cycle of 20-60-20^{o}C for a few days.

3.2 Measurement setups, research methodology

The measurements are done using the IDAX 300 system. The setup enables impedance measurements in the frequency range from 10^{-4} to 10^{3} Hz. After some recalculations, we can obtain characteristics of relative permittivity (ε_w) and the dielectric loss factor (tgδ) as a function of frequency.

The characteristics are determined for samples of changed moisture, with the increment not greater than 0.5% H_2O in the range from 0.5 to 4.0% of water content. Each sample of a selected moisture level is investigated at different temperature values in the range from 10 to 80^{o}C. For each combination of the moisture level and the temperature value, the measurements are done on three samples.

3.3 Research results

Figures 2 and 3 present measurement results of the dielectric response (ε_w, tgδ=f(f)) of pressboard samples impregnated with mineral oil and synthetic ester MIDEL 7131, moistened respectively to the level of 0.5 and 4% by weight [9,10]. The comparison of results obtained for both the liquids and for the two moisture levels lets us find considerable differences of the characteristic's course. These results confirm the assumption that moisture patterns obtained for moistened pressboard samples impregnated with mineral oil are not suitable for the interpretation of the research results obtained by means of the FDS method for transformers filled with synthetic ester MIDEL 7131.

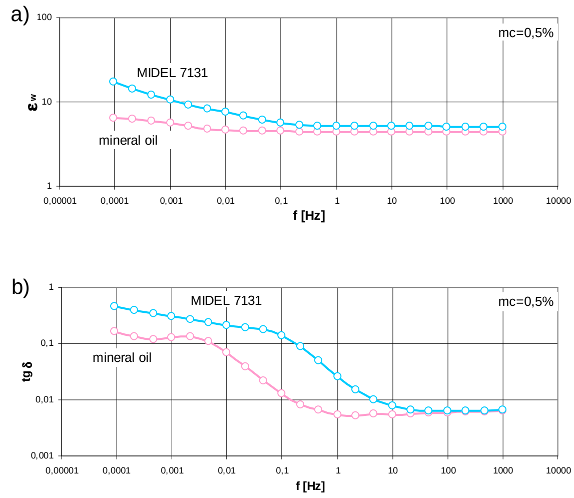

Figure 2: Dielectric response of pressboard samples of the moisture content 0.5% by weight, impregnated with mineral oil and synthetic ester type MIDEL 7131: ε_w (f) (a) and tgδ(f) (b) [9, 10]

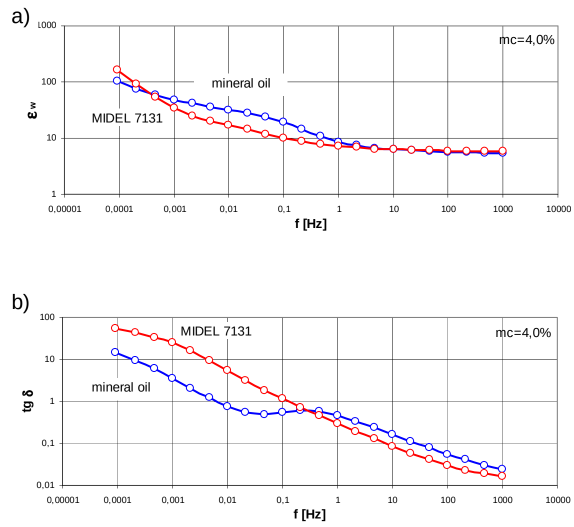

Figure 3: Dielectric response of pressboard samples of the moisture content 4.0% by weight, impregnated with mineral oil and synthetic ester type MIDEL 7131: ε_w (f) (a) and tgδ(f) (b) [9, 10]

Additionally, for the purpose of comparison, Figure 4 presents results for the pressboard impregnated only with synthetic ester MIDEL 7131 but moistened to two different levels of 0.5% and 4% by weight. A clear shift of the characteristics describing dry and moistened pressboard in the range of low frequencies, which are two orders of magnitude for the dielectric loss factor and one order of magnitude for relative permittivity, guarantees high sensitivity of the method to determine cellulose product moisture based on this kind of patterns.

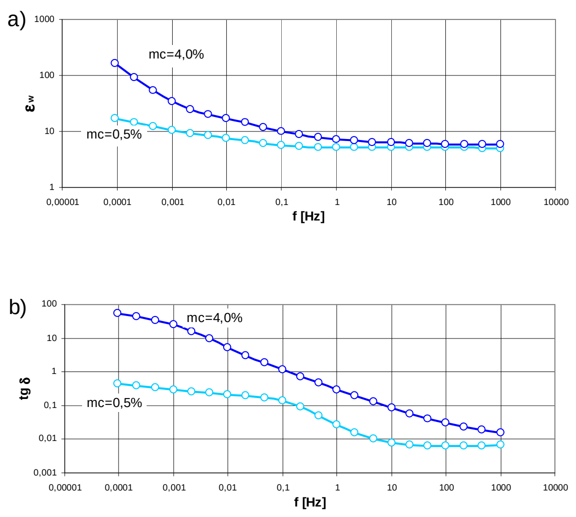

Figure 4: Dielectric response of pressboard samples impregnated with synthetic ester type MIDEL 7131, of moisture content 0.5% and 4.0% by weight: ε_w (f) (a) and tgδ(f) (b) [9, 10]

4 CONCLUSIONS

Electric permittivity (ε_W) and the dielectric loss factor (tgδ) analysed in a wide range of frequency can be used in diagnosing the moisture state of the insulating system (pressboard-synthetic ester MIDEL7131).

We can observe an increase of ε_w and tgδ of the investigated object with decreasing voltage frequency. For the purpose of diagnosing, the analysis of the dielectric response in the frequency range from 10^{-2} to 10^{-4} is the most advantageous. This range can be treated as a diagnostic band.

Eight-fold changes of the moisture levels of the investigated object are accompanied by dielectric response changes of two orders of magnitude. It is a very good situation because it affects the sensitivity of the diagnostic method. Using this method, we can observe moisture changes of the order of 0.1 percentage point.

The accuracy, and credibility of the method depend, however, to a large extent, on moisture pattern credibility. Therefore it is a key issue in this kind of diagnostics to own good patterns.

5 ACKNOWLEDGMENTS

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