1. Krzysztof WALCZAK[1], 2. Hanna MOŚCICKA-GRZESIAK[1], 3. Piotr PRZYBYŁEK[1], 4. Hubert MORAŃDA[1], 5. Radosław SZEWCZYK[2]

Poznan University of Technology, Institute of Electric Power Engineering (1), DuPont (2)
ORCID: 1. 0000-0002-0722-9495; 2. 0000-0002-0903-9417; 3. 0000-0002-5258-5894; 4. 0000-0001-7961-5814; 5. 0000-0003-3825-2409

doi:10.15199/48.2021.08.04

Frequency Dielectric Response of Aramid Enhanced Cellulose Paper in Aspect of Its Water Content Determination

Abstract. *This article compares the dielectric response in the frequency domain of the aramid enhanced cellulose paper and cellulose paper. Based on results of the measurements, the characteristic of tanδ, measured at 10^{-3} Hz, in function of moisture content of the samples was created. The physical basis of this relationship has been explained. Using this characteristic, it is possible to determine the moisture content of aramid enhanced cellulose papers of different thickness, i.e. with possibly different percentage of cellulose and aramid, without the need for moisture patterns.*

Streszczenie*. W artykule przedstawiono porównanie odpowiedzi dielektrycznej w dziedzinie częstotliwości papieru celulozowego wzmocnionego aramidem znanego pod nazwą Nomex 910 oraz papieru celulozowego. Na podstawie charakterystyk tgδ w zależności od częstotliwości stworzono charakterystykę tgδ przy 10^{-3} Hz w zależności od zawilgocenia próbek. Wyjaśniono fizyczne podstawy tej zależności. Wykorzystując tę charakterystykę można wyznaczyć zawilgocenie materiałów celulozowych wzmocnionych aramidem o różnej grubości, tzn. o różnej procentowej zawartości celulozy i aramidu bez konieczności posiadania wzorców zawilgocenia.(****Odpowiedź dielektryczna częstotliwościowa materiału celulozowego wzmocnionego aramidem w aspekcie wyznaczania jego zawilgocenia****).*

Keywords: oil-paper insulation, aramid insulation, dielectric response, water content in insulation.
Słowa kluczowe: izolacja papierowo-olejowa, izolacja ar amidowa, odpowiedź dielektryczna, zawartość wody w izolacji.

Introduction

The aim of the research is to analyze the dielectric response in the frequency domain of the cellulose paper enhanced with aramid in aspect of determining its moisture content.

The subject of our research is aramid enhanced cellulose paper Nomex® 910. It is a unique three-layer material. The two outer layers are made of a blend of aramid and cellulose, while the inner layer is made of high-quality cellulose. This material has some physical and electrical properties better than cellulosic materials and is much cheaper than pure aramid papers, like Nomex® 410 or Nomex® 926. It is intended for use in oil filled distribution and power transformers.

The biggest advantage of cellulose paper enhanced with aramid is its increased thermal capability. Pure aramid paper has a thermal class up to 180 °C (based on DuPont Nomex® paper tested in oil), while non-upgraded cellulose (Kraft) has the thermal class of 105 °C. Aramid enhanced cellulose paper reaches 130 °C thermal class in mineral oil. Transformers with cellulose insulation enhanced with aramid can be designed for higher working temperature and longer lifetime. They can also bring other technical advantages [1,2]. Selected physical, electrical and thermal properties of aramid enhanced cellulose paper are better than cellulose paper, what makes aramid enhanced paper an attractive alternative in the design of transformers [3].

Moisture of the transformer insulation is a very serious operational problem. There are two main reasons for insulation wetting, namely tank leaks and the cellulose aging process accompanied by water release.

Moisture insulation increases the probability of dielectric breakdown in solid insulation, but the most serious threat is the phenomenon of water vapour release (bubble effect). This phenomenon is typical for paper-oil insulation systems. It involves the rapid release of water from wet cellulose insulation after exceeding the critical temperature. This phenomenon has been identified and described in the fundamental Oommen publication [4] and others [5, 6]. One of the results of bubble effect is the pressure increase in the tank, which can lead to an explosion and fire of the unit.

At a water content in cellulose of up to 9%, water is bound to cellulose by physical adsorption. With higher water content in cellulose, it is also present in capillary and free form [7].

In case of power transformers in service, the real moisture level of insulation reaches 4% [7]. In this situation, the moisture content is determined mainly by the phenomenon of physical adsorption. In turn, the release of water is driven by the laws of desorption.

Aramid paper, compared to cellulose paper, shows much less water adsorption. The amount of water adsorbed on the surface of cellulose and aramid fibers depends on the polarity of the material. A simple measure of material polarity is an electrical permittivity. For comparison, the relative permittivity of aramid is 3.6, while cellulose 5.8.

If we condition samples made of cellulose paper and aramid paper in identical conditions, the humidity of aramid samples is about 30% lower than that of cellulose paper samples [9]. Aramid enhanced cellulose paper, which is the subject of our research, exhibits less moisture than cellulose paper, but more than aramid paper after conditioning in identical conditions.

Unfortunately, in aramid the bubble effect occurs at a lower temperature than in cellulose with the same water content. With a lower polarity of aramid, the energy of bonds of water layers adsorbed on fibers is smaller, hence the desorption of water requires lower temperature. In turn, if the samples of cellulose and aramid paper are conditioned in identical conditions, as a result of which the water content in them will be different, then the bubble effect initiation temperature for both materials is very similar [9].

Summarizing, in aramid paper the risk of bubble effect occurrence is the same as in cellulose paper and should be taken as seriously as the moistening of cellulose paper.

In this situation, it is important to develop a reliable method for determining the moisture content of the cellulose enhanced with aramid insulation system.

Determining the moisture content of insulation using DFR method

Currently, one of the most recognized and reliable method for determining moisture content in cellulose insulation is based on the use of dielectric response in the frequency domain (DFR) [10,11]. This method was used in the international research project REDIATOOL [12,18] implemented jointly in Poland, Germany and Sweden in years 2003-2006. In the project 161 transformers were tested. This method uses moisture patterns that depend on electric permittivity and dielectric loss factor at the voltage frequency in a wide range from 10^{-4} to 10^{3} Hz. In the frame of REDIATOOL project the great database of patterns for several moisture levels of cellulose insulation (0.6-4.0% H_2O) and several temperature values (20-80 °C) was created.

In this article, the possibility of determining the moisture content of aramid enhanced cellulosic materials was analyzed using the DFR characteristics, but without the need for moisture patterns.

Test object and research stand

Figure 1 shows the structure of the tested cellulose paper enhanced with aramid. This material is produced in several thicknesses. Each material may have a slightly different ratio of aramid content to cellulose content for optimization of thermal and mechanical properties. Naturally, the physical and electrical properties of papers in different thicknesses may vary slightly.

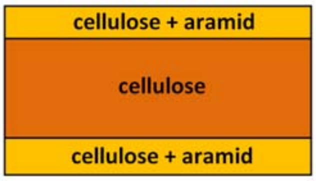

Fig.1. The structure of aramid enhanced cellulose paper

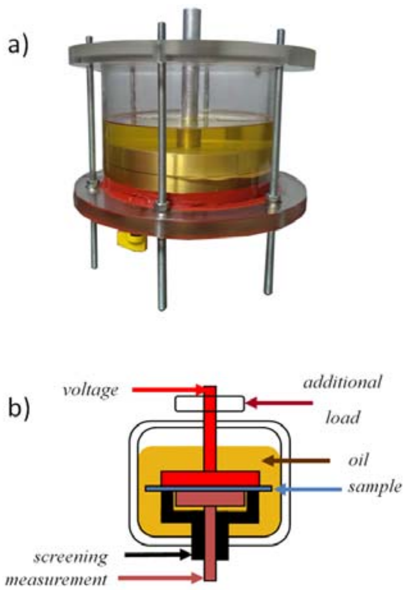

Fig.2. Test chamber (a) and an electrode system (b).

The objects of the study were cellulose paper enhanced with aramid of 0.25 mm thickness and, for comparison, cellulose paper manufactured by Krempel (Germany), 0.25 mm thick. The samples for the lowest moisture content (Set 1) were dried in vacuum chamber (90±5 °C, 0.3 mbar, 16 h), and then they were impregnated with mineral oil. The parameters used in the procedure were determined by the capabilities of the drying system (vacuum pump and heaters), and the adopted drying time resulted from previous experiments. Finally, their water content was determined by means of KFT (Karl Fischer Titration) method. The other two sets of samples with higher moisture levels were simultaneously conditioned in a climatic chamber. The samples were moistened until equilibrium was reached, and then their moisture content was determined using the KFT method. As a result, by changing the conditions in the climatic chamber, two sets (Set 2 and Set 3) of samples were obtained (Table 1).

Table 1. Water content in paper samples

Kind of paper	Water content [%]		
	Set 1	Set 2	Set 3
Nomex® 910	0.10%	2.98%	4.64%
Cellulose paper	0.27%	3.49%	5.25%

It can be seen that under the same conditions maintained in the climate chamber, the water content in cellulose and Nomex® 910 samples was different. Of course, this is due to the different polarity of these materials and, consequently, the different adsorption properties.

The Megger IDAX 300 (Megger Ltd, United Kingdom, Dover) measuring system was used in the research. The range of frequency of measurement voltage in the system is from 10^{-4} to 10^{3} Hz.

Figure 2 shows a test chamber with an electrode system.

Research results and discussion

Figure 3 shows the dependence of tan*δ* on frequency of the test voltage for all tested samples.

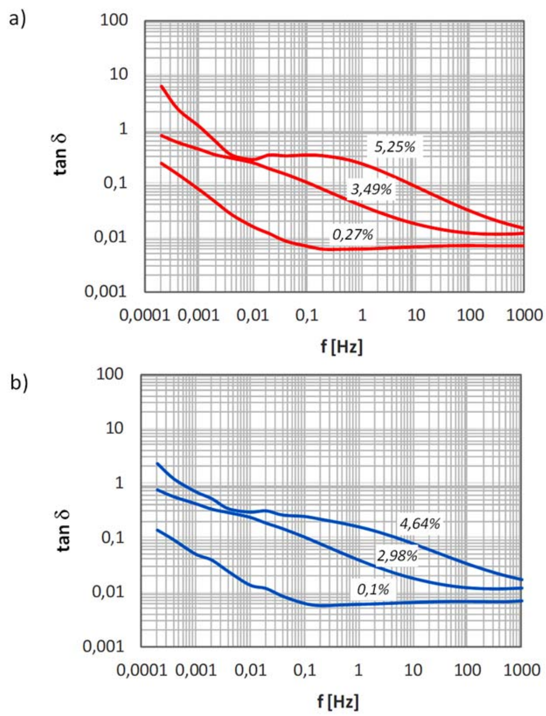

Fig.3. Dielectric response of cellulose paper (a) and aramid enhanced cellulose paper (b) with different moisture content; samples thickness 0.25 mm; measurements taken at 23 °C.

The loss factor tan*δ* depends on the active and reactive components of the current. In different frequency ranges, other phenomena determine the value of the active component of the current. At high voltage frequency, active current is mainly due to polarization losses, while at very low frequency, in the order of 10^{-3} Hz, active current is the result only of the electrical conductivity of the material. The active current to cover the polarization losses is practically zero. It is known that the electrical conductivity of fibrous materials depends on their moisture, so it was decided to check the dependence of tan*δ* at 10^{-3} Hz on the moisture of the samples. This relationship is shown in Figure 4.

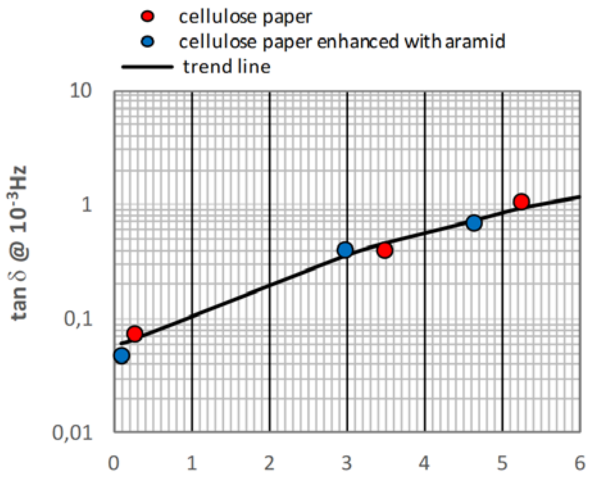

Fig.4. Dependence of dielectric loss factor tanδ on the water content of cellulose paper and aramid enhanced cellulose paper (0.25 mm thickness, measured at frequency 10^{-3} Hz and temperature 23 °C)

It can be seen that there is a functional dependence of tanδ at 10^{-3} Hz on the moisture content of the samples. The same function is valid for both: aramid enhanced cellulose paper and cellulose paper samples. This state can be explained based on the surface and cross-conduction mechanism of water-containing fibrous materials immersed in a liquid dielectric.

A water adsorption layer, composed of several monomolecular packed layers, is formed on the surface of cellulosic and aramid fibers. The number of these layers is greater the greater the polarity of the fibrous material. The water adsorption layer is constant in time and in space and does not participate in the current conduction mechanism [13].

In the vicinity of the adsorption layer, a diffusion layer is formed in the liquid dielectric. This layer contains sodium hydroxide (NaOH), which is a residue from the process of separating cellulose from other wood components. Sodium hydroxide dissociates in contact with water ($NaOH \rightarrow Na^+ + OH^-$). The formed Na^+ sodium ions combine with water dissolved in liquid dielectric and take part in current conduction. As the moisture content of the material increases, we observe an increase in electric current. The value of the tanδ factor at a frequency of 10^{-3} Hz depends on the electrical conductivity only, and therefore does not depend on the type of fibrous material, but only on its moisture.

The characteristics presented in Figure 4 can be easily used to determine the moisture content of a system with an insulation made of aramid enhanced cellulose paper without the need for moisture patterns. With using the IDAX 300 measuring system, we determine the characteristics of tanδ = f(f), read the value of tanδ at a frequency of 10^{-3} Hz, and then find the material moisture value on the curve. The obtained characteristics can be used to both cellulose and aramid enhanced paper. Hence the conclusion is that it can be used to determine the moisture content of Nomex® 910 material of various thickness, i.e. with different percentages of cellulose and aramid. The characteristic in Figure 4 has been determined for a measuring temperature of 23 °C. In the future, a method of converting the results obtained at different temperatures could be developed.

Conclusions

The problem of moisture in cellulose paper enhanced with aramid should be taken as seriously as moisture in cellulose paper.

Based on the research results, the method of determining the moisture content of the aramid enhanced cellulose insulation based on the analysis of the dielectric response in the frequency domain was presented.

There was found a functional dependence of tanδ at 10^{-3} Hz on the moisture content of the samples. The function is valid for both: aramid enhanced cellulose paper and cellulose paper samples. This state can be explained based on the surface and cross-conduction mechanism of water-containing fibrous materials immersed in a liquid dielectric.

The characteristic presented in Figure 4 can be used to determine the moisture content of cellulose papers enhanced with aramid at different thicknesses, even if having slightly different ratio of aramid to cellulose weight.

This research was funded by the Ministry of Science and Higher Education for statutory activities No 0711/SBAD/4456. Material test samples provided by DuPont and Krempel

***Autorzy**: dr hab. inż. Krzysztof Walczak, profesor uczelni, Politechnika Poznańska, Instytut Elektroenergetyki, ul. Piotrowo 3a, 60-965 Poznań, E-mail: krzysztof.walczak@put.poznan.pl; prof. dr hab. inż. Hanna Mościcka-Grzesiak, Politechnika Poznańska, Instytut Elektroenergetyki, ul. Piotrowo 3a, 60-965 Poznań, E-mail: hanna.moscicka-grzesiak@put.poznan.pl; dr hab. inż. Piotr Przybyłek, profesor uczelni, Politechnika Poznańska, Instytut Elektroenergetyki, ul. Piotrowo 3a, 60-965 Poznań, E-mail: piotr.przybylek@put.poznan.pl; dr hab. inż. Hubert Morańda, profesor uczelni, Politechnika Poznańska, Instytut Elektroenergetyki, ul. Piotrowo 3a, 60-965 Poznań, E-mail: hubert.moranda@put.poznan.pl; dr inż. Radosław Szewczyk, DuPont, ul. Postępu 17B, 02-676 Warszawa, E-mail: radoslaw.szewczyk@dupont.com*

LITERATURA

[1] Szewczyk R., Marek R.P., Ballard R.C., Duart J.C., Vercesi, G. Innovative insulation materials helping in cost reduction of modern transformers, proceedings of the 25th International Conference on Electricity Distribution CIRED, Madrid, 3-6 June 2019, Paper No 2108
[2] Szewczyk R., Duart J.C., Trifigny P., Mitigation of lock-in effect for compact substations with transformers meeting future EU efficiency regulations, proceedings of the 25th International Conference on Electricity Distribution CIRED, Madrid, 3-6 June 2019, Paper No 2089
[3] Johnson Marek R.P., Calil W., Galhardo L., Souza A., Practical verification of a high temperature insulation system for power transformers, proceedings of the IX WORKSPOT - International Workshop on Power Transformers, Equipment, Substations and Materials, Brasil, 25-28 November 2018
[4] Oommen T.V., Lindgren S.R, Bubble evolution from transformer overload, proceedings of the Transmission and Distribution Conf. Exposition, IEEE/PES, 1 (2001), pp. 137-142
[5] Sakai M., Maki K., Taniguchi Y., Daikuhara N. and Yanabu S., A Research of Critical Temperature on Bubble Formation under Overloaded Oil-Immersed Transformer, *Trans. Inst. Electr. Eng. Japan*, 121-B (2001), 500-506
[6] Lu Y., Chao N., Zhao T. Tong Y., Jia C., Mechanism and numerical model of bubble effect in oil-paper insulation based on microtubule model, IEEE Trans. Dielectr. Electr. Insul. (27) 2020, n. 5, 1529-1537
[7] Prosiński S., Chemia drewna, PWRiL, Warsaw, Poland, 1984

[8] Gielniak J., Graczkowski A., Moranda H., Przybylek P., Walczak K., Nadolny Z., Moscicka-Grzesiak H., Gubanski S.M., Feser K., Moisture in cellulose insulation of power transformers: statistics, IEEE Trans. Dielectr. Electr. Insul. (20) 2013, n. 3, 982-987
[9] Przybylek P., A comparison of bubble evolution temperature in aramid and cellulose paper, proceedings of the IEEE International Conference on Solid Dielectrics, Bologna, Italy, June 30 – July 4, 2013
[10] Gubanski S.M., Boss P., Csepes G., Houhanessian V.D., Filippini J., Guuinic P., Gafvert U., Karius V., Lapworth J., Urbani G., Werelius P., Zaengl W.S., Dielectric response methods for diagnostics of power transformers. Report of the TF D1.01.09. Brochure of CIGRE No 254, 2002
[11] Gubanski S.M., Blennow J., Holmgren B., Koch M., Kuechler A., Kutzner R., Lapworth J., Linhjell D., Tenbohlen S., Werelius P., Dielectric response diagnoses for transformer windings, Brochure of CIGRE No 414, 2010
[12] Gubanski, S.M., Blennow J., Karlson L., Feser K., Tenbolen S., Neumann C., Moscicka-Grzesiak H., Filipowski A., Tatarski L., Reliable Diagnostics of HV Transformer Insulation for Safety Assurance of Power Transmission System. REDIATOOL - European Research Project, CIGRE General Session D1–207, 2006, pp. 15
[13] Young D.M., Crowell A.D., Physical Adsorption of Gases, Butterworth & Co Limited, London, England, 1962