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THE ANALYSIS OF THE THERMAL AND DIELECTRIC PROPERTIES OF HIGH VOLTAGE INSULATING MATERIALS WITH THE ADDITION OF ALUMINIUM OXIDE

This article describes the influence of thermal and dielectric properties of materials to properties of electrical insulating systems in high voltage electrical equipment. The aim of this experiment is to improve the thermal and dielectric properties of electrical insulating (composite) materials using micro fillers of aluminium oxide Al_2O_3. Supplement of fillers of aluminium oxide with better thermal conductivity to the electrical insulating systems can be modified to increase their thermal conductivity. Improving the thermal conductivity of electric insulation by addition of micro- or nanofillers and in the same time not adversely affecting the dielectric properties is the objective of the study. Paper is presenting the results measured on prepared samples. Improved thermal conductivity is compared with other dielectric properties as: dissipation factor temperature dependences, resistivity and dielectric spectroscopy. To determine the dielectric insulating properties the following characteristics were measured: tanδ versus temperature from 110°C to 150°C, absorption and resorption currents, volume resistivity. Furthermore, this article describes analysis of moisture and conductivity the material by dielectric spectroscopy.

Keywords: electroinsulation systems, dielectric properties, epoxy resin, aluminum oxide, temperature, frequency

1. Introduction

The electroinsulation systems based on mica and their application in high voltage dry-type transformers or rotating machines had been optimized over the last 60 years. Generally, the components of the electroinsulation systems are made from mica, epoxy resin (or any possible polyester resin or silicone resin) and glass fabric or other materials (as polyimide film, polyester film).

High voltage winding of dry transformers is made from one coil of aluminium strip or wire. The coils are wound with an insulating layer, stored in a special format, in which the after thermal adjustment is filled epoxy resin. After the polymerization it gives a compact winding with the corresponding thickness of the insulation.

This technology enables the production column, whose driver is protected from moisture and other aggressive external influences. Dry transformers need for cooling only air. The coolant such as oil can not get into environment. Furthermore, catch pits or tubs are eliminated. The resin has excellent flame retardant and incombustible properties, but resin has a low thermal conductivity. Materials with low thermal conductivity form a barrier to the flow path of heat from winding. The aim of thermal calculations is to define the medium and maximum temperature rise in individual parts of dry transformers, which are in direct contact with the electrical insulation material. With increased load in the temperature of active parts, this may lead to increased stress of electric insulation systems, or their destruction.

In this study, we prepared composite material epoxy with micro particles of aluminum oxide (two set of samples). This composite materials combine the benefits of the individual components and allow generate new materials with better properties than those of individual components. If it were possible to find new materials with higher thermal conductivity, then would be possible to increase heat transfer, alternatively encumber of higher values of current or reduce the size of the transformers (e. g. thinner electrical insulation layer) and thus change the price of transformers.

2. Production of samples

By increasing the thermal conductivity of electrical insulating system one can accelerate the flow of heat from the windings to the cooling medium. The increased of thermal conductivity can be made by adding fillers with a higher thermal conductivity, in our case, by the addition of aluminium oxide Al_2O_3 (λ = 25-40 ($W \cdot m^{-1} \cdot K^{-1}$)) [1]. Thermal conductivity of the individual material that are most commonly used to manufacture the electroinsulation systems, are presented in Table 1 [1]. As

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seen from Table I, these materials have relatively low thermal conductivity.

TABLE 1

Thermal conductivity of materials used in electroinsulation systems

Materials	λ ($W \cdot m^{-1} \cdot K^{-1}$)
Epoxy resin	0.2
Glass fiber	0.8-1.2
Mica	0.3-0.6

Using this method was produced two set of samples. The first set of samples was prepared using from epoxy resin with the trade name LV EPOXYLITE 3750 with the addition of 0.5% of particles of mica, glass fabrics and the aluminium oxide Al_2O_3 in proportions shown in Fig. 1. For the production of further sets we used epoxy resin with the trade name EPOXYLITE TSA 220 with the addition of 0.5% of particles of mica, glass fabrics and the aluminum oxide Al_2O_3 in an amount (2%, 4%, 6%, 8% and 10%), which can be seen in Fig. 1.

3. Measurement of the thermal conductivity

Measurement of the thermal conductivity was in accordance with the ISO 22007-2:2015 [2]. This standard gives the plate method and conditions of its use for the determination of the thermal conductivity test samples in a steady thermal condition.

Generally, the resulting value of the thermal conductivity of the material is higher than the thermal conductivity of the individual components of the composite material.

The value of thermal conductivity increases with the addition of Al_2O_3 in an amount 2%, 4%, 6%, 8% and 10%, see Fig. 1. Increasing the thermal conductivity may be due to the ability and the size of the forces, which are Al_2O_3 bound particles. Thermal conductivity depends on the ability of a substance to transmit heat movement from one particle to another. If the sample has more Al_2O_3 particles, then it has the higher thermal conductivity. Moreover, in our samples the heat distribution is present in the polymeric chain, glass fiber and alumina particles.

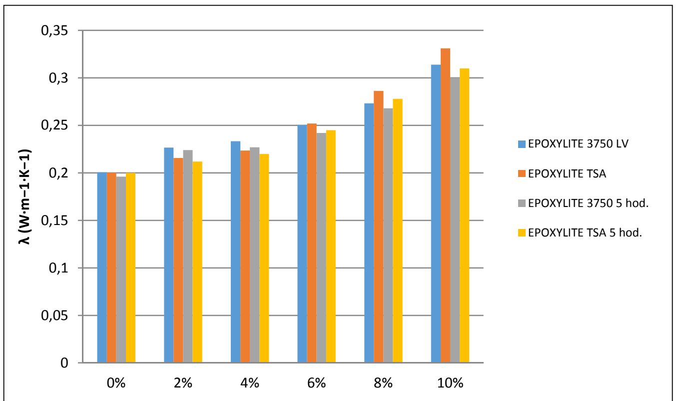

Fig. 1. Thermal conductivity of the samples filled Al_2O_3

Fig. 1 shows the results of measurement of thermal conductivity after 5 hours of aging at 130°C. Coefficient of thermal conductivity after 5 hours of aging has lower values compared with the measurement results from aging, which can be caused by moisture content closed in microscopic tubes sample before aging. Moisture material may affect the value of the thermal conductivity. An increase of moisture the material increases and thermal conductivity. After aging, the samples are dried. The air has a lower thermal conductivity than water.

Thermal conductivity of materials increases with temperature. It may be caused by spread of heat conduction in the solid particles of aluminum oxide, which can be increased with increasing temperature [3]. Electrical insulating systems of high-voltage machines are devices operated at higher temperatures, so the measurement of the thermal conductivity, depending on the temperature, will be addressed in a further research.

4. Measurement of tanδ versus temperature

As expected, it is possible to modify thermal conductivity of the sample with the addition of Al_2O_3, but it is necessary to take into account dielectric properties of the sample.

Measurement of the dependency of tanδ on temperature was carried out at voltage 500 V, power frequency 50 Hz and temperature 20°C. The measurement of dissipation factor was carried out according to IEC 60250 [4].

Fig. 2 shows result of measurement of tanδ versus temperature set from 110°C to 150°C. It can be seen that samples produced with the epoxy resin EPOXYLITE 3750 LV with the addition of 8% of Al_2O_3 have the same characteristic as the samples with addition of 10% Al_2O_3 and have the greatest values of tanδ. The produced multicomponent samples are inhomogeneous materials and by their very nature contribute to increase the dielectric losses. The movement of free and bound carriers in the samples, and the polarization mechanisms are the other possible causes leading to an increase in tanδ of the sample with a variety of alumina. Furthermore, we can see the same behavior trends for a sample of 6% and 2% where the observed lower values of tanδ. Samples with 4% of Al_2O_3 have the lowest values of tanδ. Samples manufactured without adding Al_2O_3 paradoxically do not have the lowest value of tanδ.

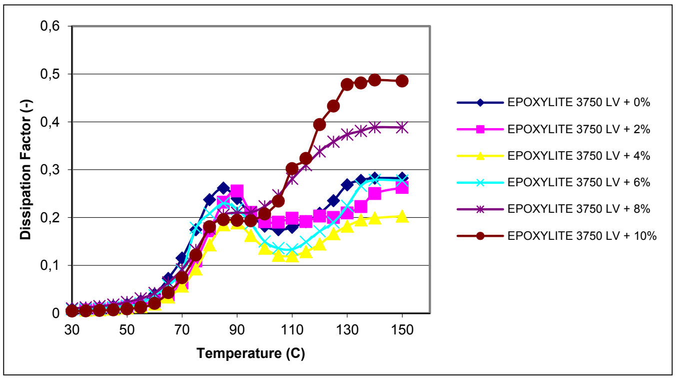

Fig. 2. Measurement of tanδ versus temperature from 110°C to 150°C

Further attention will be paid to the chart area (Fig. 3) from temperature 30°C to 50°C, in which we can see that the lowest values of tanδ has a sample made of pure resin EPOXYLITE 3750 LV. Larger values of tanδ is assumed to have the samples with added Al_2O_3.

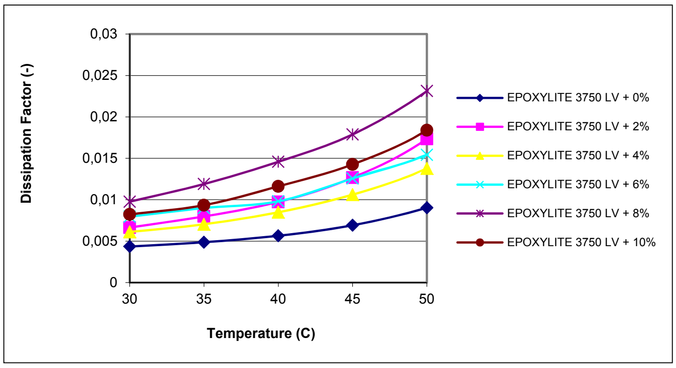

Fig. 3. Measurement of tanδ versus temperature from 30°C to 50°C

The temperature range from 110°C to 150°C is shown in Fig. 4. It can be seen from this figure, that samples produced with the epoxy resin EPOXYLITE TSA with addition of 10% of Al_2O_3 have the highest value of tanδ. Samples with 8% of Al_2O_3 have similar shape (up to 90°C tanδ rises then falls) as samples with the addition of 0% Al_2O_3. Furthermore, we can observe the same behavior trends for sample 6% and 2% where lower values of tanδ are observed. Samples with 4% of Al_2O_3 have the lowest values of tanδ.

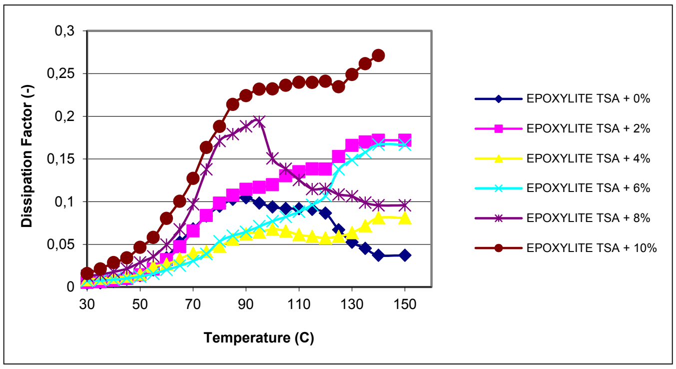

Fig. 4. Measurement of tanδ versus temperature from 110°C to 150°C

Further attention will be paid to the chart area (Fig. 5) from 30°C to 50°C, where we can see that the lowest values of tanδ has the sample made of pure epoxy resin EPOXYLITE TSA. Samples with added of Al_2O_3 have a larger values of tanδ as assumed.

The graphs presented in Fig. 2 and Fig. 5 (tanδ vs. temperature ranging from 30°C to 150°C) do not show the effect of the fillers on the tanδ versus temperature, but follow the same trend behaviour in all samples where we observe lower tanδ from 90°C. All samples were cured at 160°C (for 3-6 hours). It is assumed that the samples were not hardening. In practice, electrical insulation systems harden at startup operation of the electrical equipment.

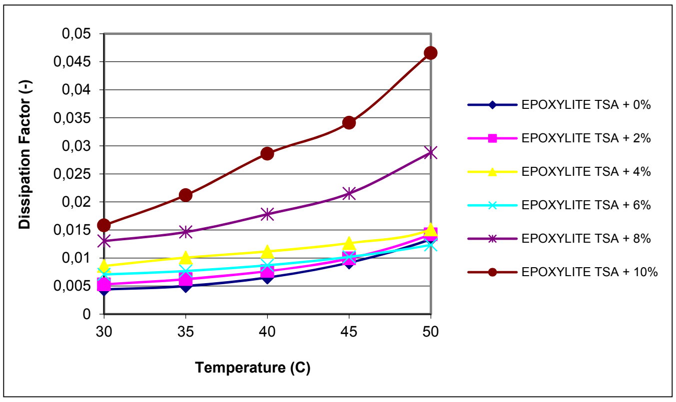

Fig. 5. Measurement of tanδ versus temperature from 30°C to 50°C

The service life of electrical equipment is primarily intended life of its electrical insulating system. Lifespan of electrical equipment is around twenty to sixty years. Durability of an electrical insulating system depends on the vibrations, humidity, impurities and other factors. The most critical quantity influencing life of electrical equipment is temperature. Electrical installation system of electrical equipment (for example air-cooled turbo generators, transformers) today works in temperature class F (155°C) or higher. Usually, the operating temperature is lower (class B (130°C), it is a long tradition of having a thermal class in reserve. Fig. 6 and Fig. 7 show the measurement tanδ depending on the temperature after 5 hours of aging at 130°C, which is the operating temperature of the electrical equipment. Measurements of tanδ versus temperature after 5 hours of aging have been carried out only up to 130°C, which is the operating temperature of the electrical equipment.

It can be seen from the graph in Fig. 6 (tanδ vs. temperature changed from 110°C to 130°C after 5 hours of aging at 130°C) that samples produced with the epoxy resin EPOXYLITE 3750 LV with the addition of 8% of Al_2O_3 have the same characteristics as the samples with addition of 10% of Al_2O_3 and at the same time have the largest values of tanδ as in Fig. 2. Samples with 4% of Al_2O_3 have the lowest values of tanδ, as in Fig. 2. The value of tanδ increases up to 130°C, see Fig. 6.

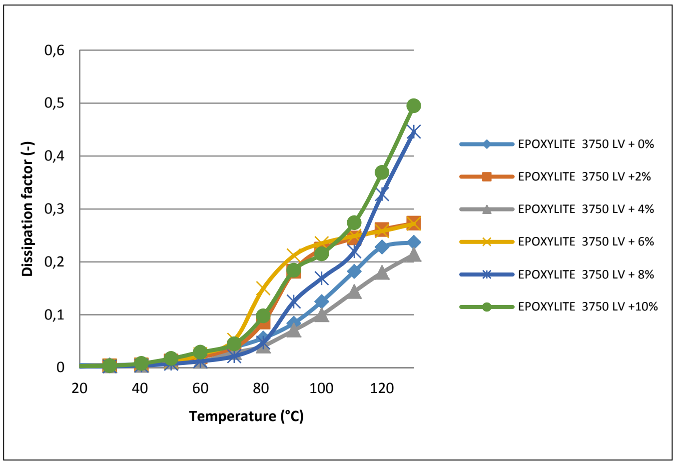

Fig. 6. Measurement of tanδ versus temperature from 110°C to 130°C (after 5 hours of aging at 130°C)

In Fig. 7 we observe the tanδ grows up to 130°C. The sample with the addition of 8% and 10% of alumina begins to decrease slightly.

From the graph in Fig. 6 and Fig. 7 we see that after aging waveforms tanδ changed (continuously grow to 130°C) compared with the measurement before aging (Fig. 4). Therefore, we assume that during operation of the electrical device reaches the maximum, which is a corresponded thermal class electrical insulating system. We expect that after the final hardening the tanδ decrease with operating time of the electrical equipment and can achieve even lower values of tanδ than at the start operation of the new electrical equipment.

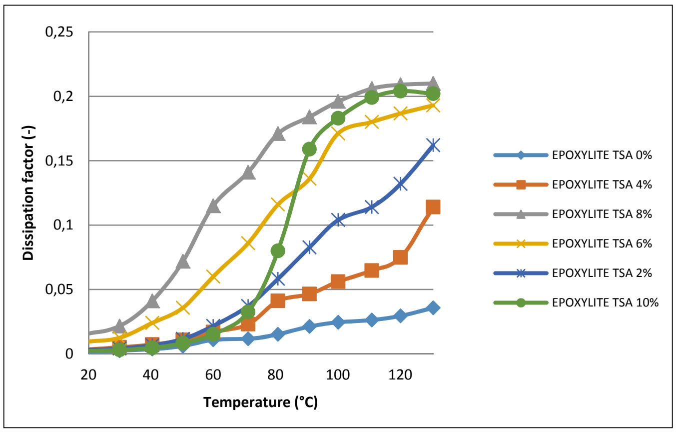

Fig. 7. Measurement of tanδ versus temperature from 110°C to 130°C (after 5 hours of aging at 130°C)

5. Measurement of absorption and resorption currents

Furthermore, the samples were measured for absorption and resorption currents (voltage 500 V) (Fig. 8 and Fig. 11).

Fig. 8 shows a larger proportion of slow polarization for sample with higher amounts of the filler of Al_2O_3 (10% and 8%). It can be caused by uneven dispersion of the filler Al_2O_3 and the formation of clusters of particles Al_2O_3 in a matrix epoxy resin. Paradoxically low filler concentration 2% of Al_2O_3 in matrix EPOXYLITE 3750 LV show a more rapid decrease of the absorption curve, see Fig. 8.

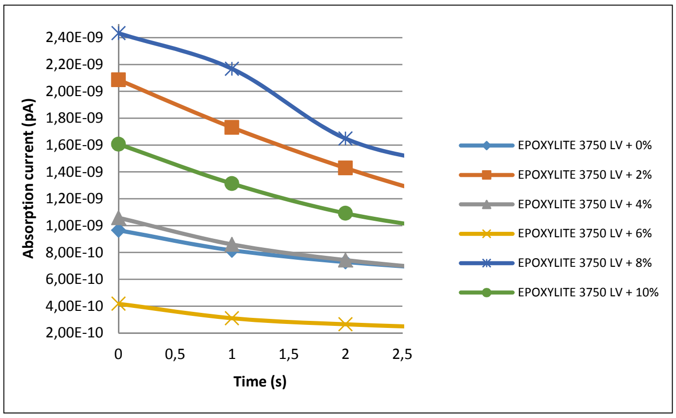

Fig. 8. Absorption currents on samples filled by Al_2O_3

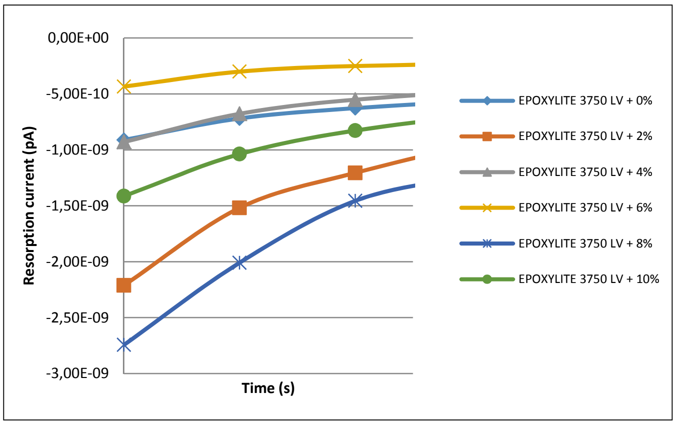

Fig. 9. Resorption currents on samples filled by Al_2O_3

From Fig. 10 is evident greater proportion of slow polarization in a sample with a variety of filler alumina 10%, which may be caused by uneven dispersal of the filler and the formation of clusters of particles of Al_2O_3. Further, from Fig. 10 can be viewed polarization mechanism for the sample with 2% and 6% of Al_2O_3 in matrix EPOXYLITE TSA 220.

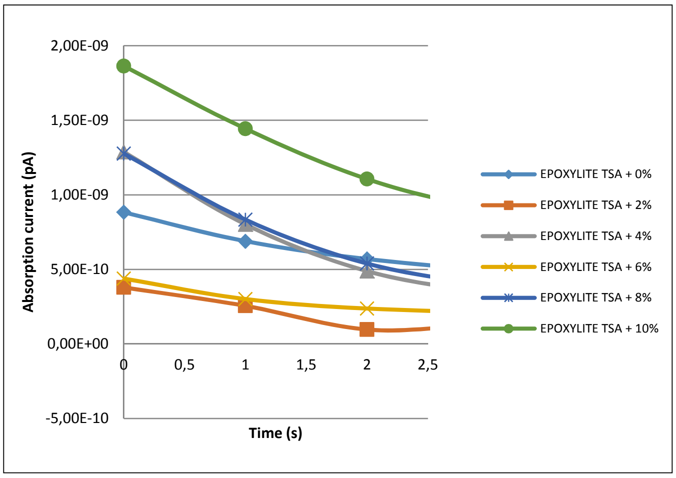

Fig. 10. Absorption currents on samples filled with Al_2O_3

Difference of permittivity between micro filler of Al_2O_3 when has higher permittivity than unfilled may lead to increase the proportion of polarization. About which course of polarization currents (in the material takes place more polarization mechanisms) determines the structure of the dielectric, the accumulation of free charge carriers e.g. interfacial inhomogeneities, impurities or air cavities. If increasing polarization of material then dielectric losses grow.

Resorption current (Fig. 11) is use for the determination of reduced resorption curves. The resorption currents are dependent on the filler concentration. Resulting points to evaluate the properties of electro insulating materials are based on the linear compensation of resorption currents. The higher the slope of reduced absorption curves the better insulating properties of the electro insulator.

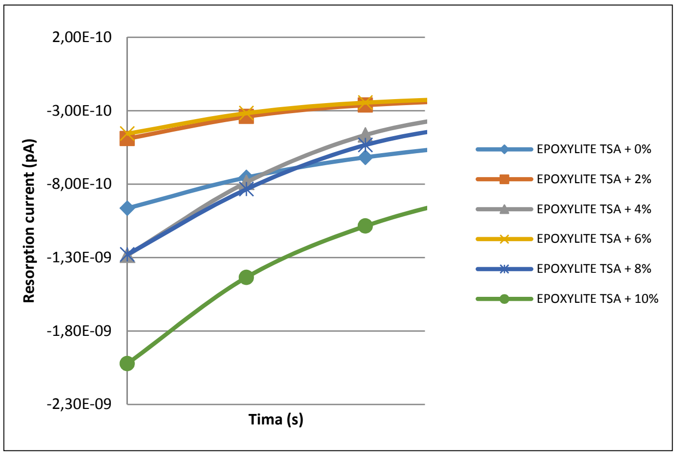

Fig. 11. Resorption currents on samples filled with Al_2O_3

6. Measurement of volume resistivity

The measurement of volume resistivity was implemented on DC voltage of 500 V, power frequency 50 Hz and temperature 20°C. The measurement of volume resistivity was carried out according to IEC 60093:1980 [5].

The results of measurement of the volume resistivity ρ_v ($\Omega \cdot$ m) are presented in Table 2. The highest values of the volume resistivity have samples made with EPOXYLITE TSA 220 with 2% and 4% of Al_2O_3 and thus the smaller the conductivity of the sample. Samples made with EPOXYLITE 3750 LV with 4% of Al_2O_3 have the highest value of resistivity compared to other samples made with EPOXYLITE 3750 LV.

The lowest values of the volume resistivity have sample made with EPOXYLITE 3750 LV s 2%, 8% a 10% of Al_2O_3 in comparison with other samples. Samples made with EPOXYLITE TSA 220 have larger values of volume resistivity compared to EPOXYLITE 3750 LV.

TABLE 2

The measurement of volume resistivity

Sample	ρ_v ($\Omega \cdot$ m)
EPOXYLITE 3750 LV + 0%	7.26E+14
EPOXYLITE 3750 LV + 2%	3.76E+14
EPOXYLITE 3750 LV + 4%	2.00E+15
EPOXYLITE 3750 LV + 6%	4.84E+14
EPOXYLITE 3750 LV + 8%	3.09E+14
EPOXYLITE 3750 LV + 10%	4.46E+14
EPOXYLITE TSA + 0%	9.07E+15
EPOXYLITE TSA + 2%	2.09E+16
EPOXYLITE TSA + 4%	2.13E+16
EPOXYLITE TSA + 6%	8.81E+15
EPOXYLITE TSA + 8%	2.70E+15
EPOXYLITE TSA + 10%	9.87E+15

7. Analysis moisture and conductivity by dielectric spectroscopy

On samples EPOXYLITE 3750 LV was performed analysis of humidity and conductivity by dielectric spectroscopy (FDS method) [6].

The measurement was performed at a frequency from 0.0005 to 1000 Hz. The principle of the method is based on the monitoring of the polarization of the particles while varying the frequency over a wide band [7].

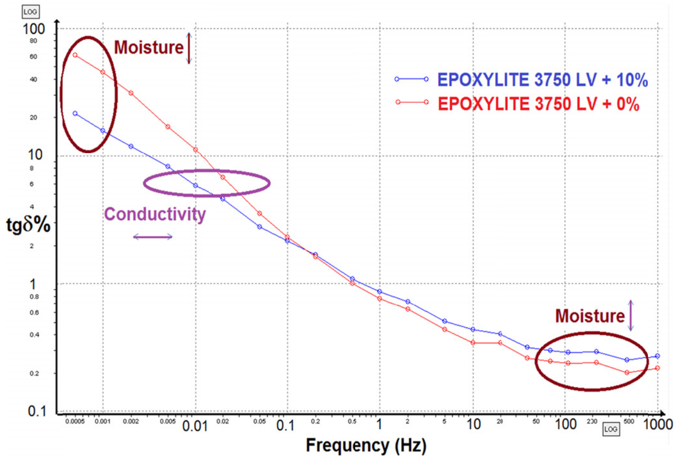

Fig. 12. Frequency analysis moisture and conductivity of samples EPOXYLITE 3750 LV

According to Fig. 12 up to 0.1 Hz sample with 10% addition of Al_2O_3 shows lower values of dissipation factor than without such addition. It shows also lower moisture sensitivity for sample with addition. Higher conductivity of sample with addition is evident from curve with lower angle.

Similar curves it is possible to measure on samples EPOXYLITE TSA 220 for temperature 40°C (Fig. 13).

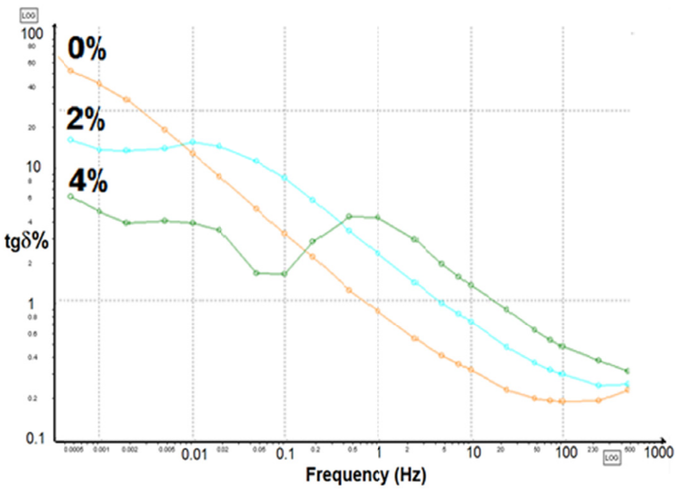

Fig. 13. Frequency analysis moisture and conductivity of samples EPOXYLITE TSA 220 for 40°C

8. Conclusion

The performed experiment showed that the value of the thermal conductivity increases with the addition of higher amounts of Al_2O_3 (Fig. 1), certain concentration improves resistivity (Table 2) and does not deteriorate the tangent (Figs. 2,4,6,7).

Samples made with EPOXYLITE 3750 LV 4% Al_2O_3, and the samples produced with EPOXYLITE TSA 220 with 4% of Al_2O_3 have the lowest values of tanδ (before aging and after 5 hours of aging).

Samples made with EPOXYLITE TSA 220 have larger values of resistivity compared to EPOXYLITE 3750 LV (Table 2) and also have lower values of tanδ.

This implies the need to use other resins or considering the use of Al_2O_3 nano fillers.

Obtained results show apparent better thermal conductivity and lower moisture sensitivity (?) of samples with addition of Al_2O_3.

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