Influence of Water on Selected Dielectric Properties of Impregnants in the Cured State

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***Abstract*—Improving the properties of impregnants used for the windings of electric rotating machines and transformers is still an actual problem that is being dealt with by many scientific institutions looking for more efficient and environmentally friendly materials. The goal is not only to increase the reliability and service life of electrical equipment, but also to optimize the production process and material base, which will lead to a reduction in economic costs. Constantly increasing requirements on the properties of impregnants are met either by introducing completely new impregnants or by modifying the original ones. In both cases, it is necessary to test their properties in order to verify the long-term stability and resistance to degradation effects. This paper presents partial results from testing the resistance of three different impregnants in the cured state to water in terms of investigation of selected dielectric properties.**

Keywords—impregnants, impregnation of electric windings, dielectric properties

I. INTRODUCTION

Solvent varnishes are formed by film-forming substances that are dissolved in specific solvents. They thus form a solution, and this solution may also contain diluents. Each solvent or thinner is intended for a specific type of impregnation varnish. Film-forming substances represent the non-volatile part of the solution, the so-called dry matter. The dry matter content in individual solution is approximately 10 to 60%. Film-forming substances are mainly represented by natural and synthetic resins [1,2].

As for the solvents, we are interested in dissolving capacity, i.e. the ability to dissolve film-forming substances. Depending on the type, solvents have different dissolving abilities. When using solvents, care is taken to ensure that the resulting varnish has the desired properties and that a smaller amount of solvent is preferred. The choice of suitable types of solvents, as well as their content, have a fundamental influence on the quality of the impregnation varnish in the hardened state. During the curing process, solvent molecules evaporate, and the lacquer thickens. The thickening of the varnish is also influenced by the cross-linkingreactions of the film-forming molecules. The liquid varnish gradually turns into a gel mixture and then into a solid varnish film. In the best case, the curing process should take place in such a way, that the mixture of solvents evaporates gradually, while the connection of the varnish will not be disturbed, and only after the solvents have evaporated the chemical curing processes will occur.

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Impregnation varnishes and resins are used to impregnate the windings of electric rotating machines and devices, as well as transformers, and to impregnate fibrous organic or inorganic insulators. Impregnation has an important function in the development of electrical machines as well as insulating materials. By combining with other insulating materials, it ensures the required properties and final product behaviour. In the case of machine windings, for which wires with fibrous insulation were used, impregnation ensures improvement of electrical parameters of the insulation. In the case when lacquered wires are used, the main task of impregnation has been to bring better mechanical properties. In general, it can be said that impregnants used for windings of electrical machines should meet the following requirements [3,4,5]:

- **Protection of the winding against negative operating factors.** Impregnation of the winding ensures protection against external environmental influences. It protects the winding against the effects of atmospheric influences such as moisture, small dust particles and other types of pollution or from various chemical influences.
- **To bind the impregnated structure mechanically.** When impregnants are applied to machine windings, the windings are mechanically connected into solid structure and thus a complete component is created. Vibrations and centrifugal forces occur during rotation in electric rotary machines. It is the mechanical strengthening of the winding that ensures its stability and protection against damage.
- **Improvement of the dielectric properties.** The machine winding might not have sufficient electrical insulation properties without the impregnation completion process. From this point of view, the main purpose of the impregnant is to increase the electrical strength.

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- **Improvement the heat dissipation.** At the beginning of the process there is a significant amount of small air cavities and porous structures in the raw insulation that have a negative effect on heat dissipation in the materials themselves, but also in the spaces between the windings of electrical machines. By applying a suitable impregnant, which will flow into all the pores and cavities, and increases the thermal conductivity of the winding structure and thus also the heat dissipation is improved.

- **Ecological requirements.** European legislation related to ecology, which significantly interferes also with the production of any electrical insulating materials, has come to the force more and more in recent years. Among the most important legislative regulations in the field of ecology concerning manufacturers of electrical equipment within the EU is Regulation of the European Parliament and the Council (EC) No. 1907/2006 on the registration, evaluation, authorization and restriction of chemicals (REACH) and on the establishment of the European Chemicals Agency [3] as well as Directive of the European Parliament and Council no. 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS) [4].

- **Economic requirements.** Of course, the economic dimension plays an important role in impregnation substances and manufacturing. Economic reality constantly forces manufacturers of electrical equipment to reduce prices, which also affects the requirements on impregnants and resins themselves. New types of impregnants with a cheaper material base and improved properties are being adapted and taken into account in order to simplify and reduce the energy consumption of the production process while preserving all important properties. The trend in the development of impregnants is to constantly improve the mentioned functions and required properties, either by changing their basic composition or by adding various additives and fillers in order to modify their properties. An example of such changes can be the increasing requirements for accelerating the curing of the impregnant, which has important impact to mass industrial production. However, it is necessary to emphasize, that any change in the formula or method of application of the impregnant can, on the one hand, lead to an improvement of the desired property, but on the other hand, it can negatively affect other important properties. From this point of view, it is necessary to test impregnants before putting them into practice, evaluate their quality from several points of view, and optimizematerials and processes.

II. Experimental and Discussion

A. Sample Preparation

The experiment of this research has been performed in the frame of cooperation between Department of Applied Electrical Engineering and Materials at Institute of Power and Applied Electrical Engineering (STU in Bratislava) and its long-standing cooperation partner VUKI a.s., research and production institution, in the field of electrical insulation materials research. The main aim of the experiment has been to test the resistance of newly prepared impregnant samples in the hardened (cured) state to water in terms of changes in selected dielectric properties. For the purpose of measurement, 3 types of impregnants were prepared and available, two identical samples of each. Samples of impregnant No. 1 (marked 1_1 and 1_2) were based on unsaturated polyesterimide resin with a reactive monomer of the 1,4-butanediol dimethacrylate type. Samples of impregnant No. 2 (marked 2_1 and 2_2) had the same basis as samples No. 1, but their composition was supplemented with an anti-corrosion additive and a nanofiller., The role of the nanofiller is to improve the thixotropic properties of the impregnant and more over to support the effect of the anti-corrosion aspects of an additive and thereby increase its increments in the windings. The composition of samples No. 3 (marked 3_1 and 3_2) consisted of an impregnant based on unsaturated polyesterimide resin dissolved in 1,6-hexanediol diacrylate.

Samples with dimensions of 100 mm x 100 mm were prepared by VUKI a.s. within the actual cooperation project. The visual appearance and difference of the examined samples can be seen in the following images shown in Fig. 1. The difference between individual samples is easily distinguish able with the naked eye. Sample No. 3 is the clearest one. The anti-corrosion admixture in sample No. 2, compared to sample No. 1, resulted in a change of the color of the impregnant resin, while this sample is more saturated, cloudier, and yellow coloring is evident to a considerable extent.

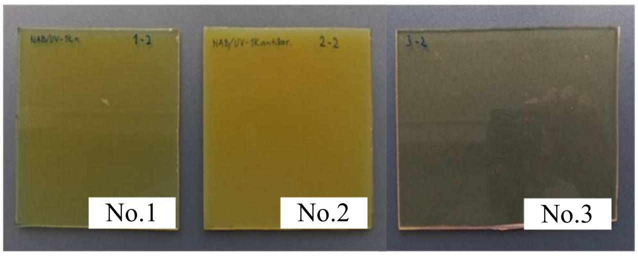
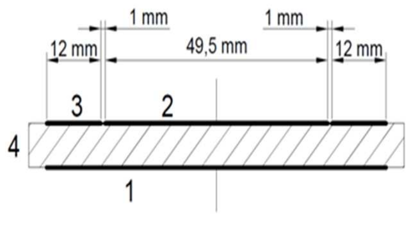


Fig. 1. Visual comparison of samples.

B. Measurement

A pressure circular three-electrode measuring system with ring-shaped protective electrode have been used. The dimensions shown in Fig. 2 were used for the purpose of measuring the selected dielectric properties. The electrode system together with the applied weights, created a pressure of 81.6 g.cm^2 on the measured sample.



1 – voltage electrode
2 – measuring electrode
3 – protective electrode
4 – measured sample

Fig. 2. A pressure three-electrode measuring system.

The resistance of the samples against to the water influence was tested in such a way that the impregnant samples were immersed in a glass container with tap water for 10 days at room temperature. After this time, the samples were taken from the water and conditioned in laboratory condition, i.e. at a room temperature of 21-22 °C and a relative humidity of 37-42% for 18 hours. Subsequently, measurements of selected dielectric properties were carried out at a temperature of 22 °C. Capacitance and dissipation factor were measured with a Tettex AG Zürich four-capacitance bridge at a frequency of 50 Hz and a voltage level of 100 V. A KEITHLEY 617 was used to measure the minute time dependence of the internal resistance at a measuring DC voltage of 100 V. The results of the water influence are shown in Fig. 3, 4 and 5. It is clear that water had a negative effect on all of the measured samples of impregnants in the cured state. The influence has been quantified as an increase of the relative permittivity, the dissipation factor and a decrease of their resistivity.

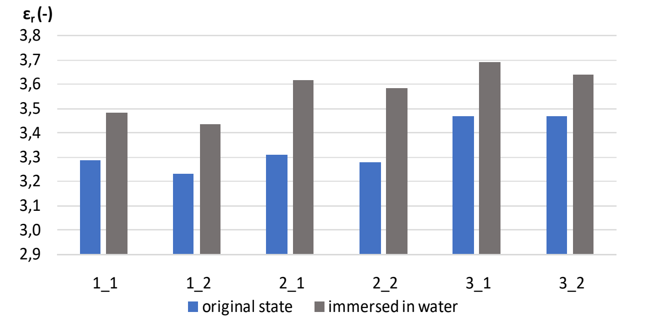


Fig. 3. Relative permitivity of samples in origin state and immersed in the water.

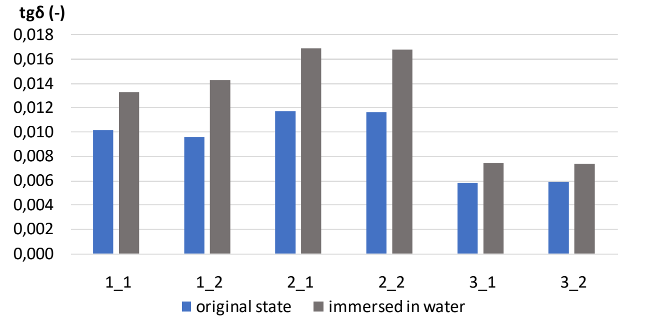


Fig. 4. Dissipation factor of samples in origin state and immersed in the water.

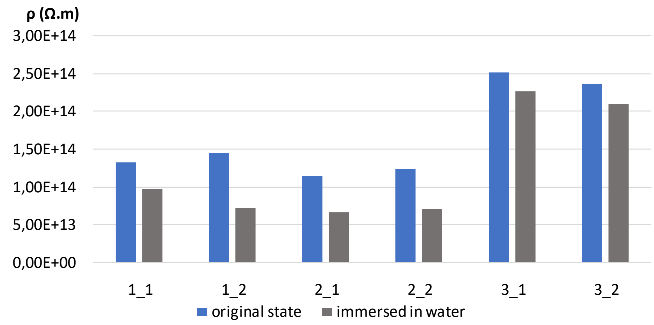


Fig. 5. Resistivity of samples in origin state and immersed in the water.

The difference has been quantified as the percentage change of the measured quantities before and after being placed/immersed in water. It can be concluded that the largest percentage change of the selected properties was demonstrated by sample No. 2. The percentage increase of the relative permittivity was slightly over 9% and the loss factor increase was about 44%. The decrease of internal resistivity was averagely about 42.1%. Samples No. 1 showed better resistance to the influence of water compared to samples No. 2. The percentage increase of relative permittivity value was approximately about 6.2%, the loss factor about 35.4% and the decrease in internal resistivity was on average 33.5%.

On the contrary, the smallest changes in the measured values due to the influence of water, out of all the measured samples, were estimated on samples No. 3. The relative permittivity increased by an average of 5.7%, the loss factor increased approximately 27% and the internal resistivity decreased by approximately only 10%.

The behavior of prepared samples has been investigated also at elevated temperature within the interval from the room temperature to 130 °C. Those measurement was performed at the beginning of the experimental procedure. We present the dependence of relative permitivity – Fig. 4, dissipation factor – Fig. 5, and resistivity – Fig. 6 of prepared samples. The behavior of all samples follows approximately the same shape, but the differences are in magnitudes of measured quantities. Taking into account the dependences shown in Fig. 6 and 7, one can suppose polar character of measured dielectrics.

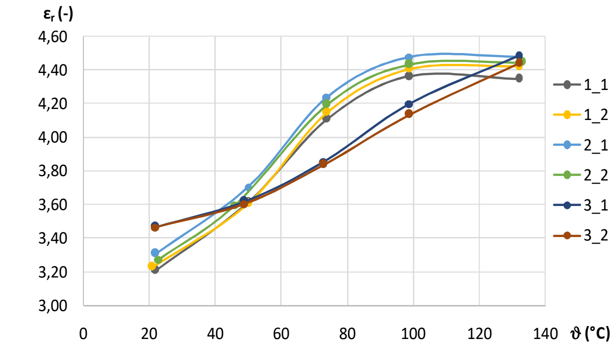


Fig. 6. Temperature dependence of relative permitivity of samples.

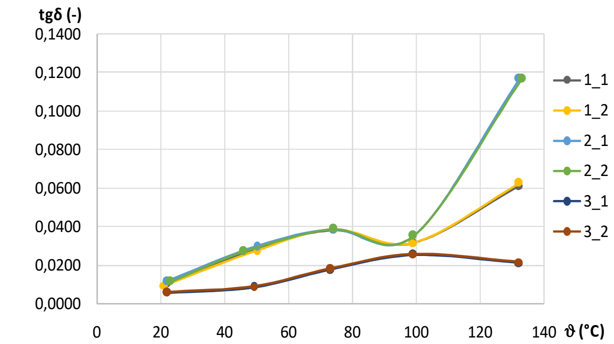


Fig. 7. Temperature dependence of dissipation factor of samples.

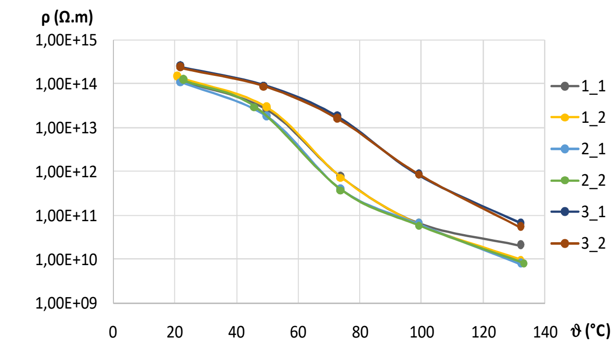


Fig. 8. Temperature dependence of resistivity of samples.

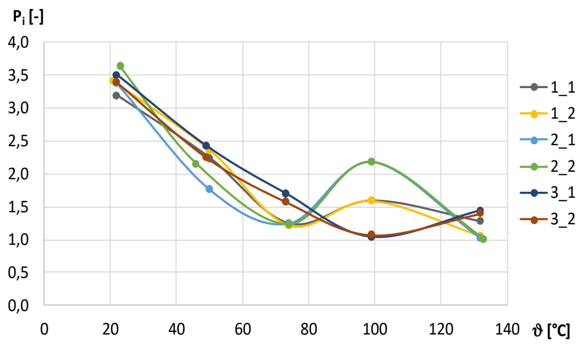


Fig. 9. Temperature dependence of polarization index of samples.

Polarization index is standard quantity which is commonly used in order to estimate polarization processes and the behavior and quality of dielectric or insulation. The dependence of polarization index on temperature is shown in Fig. 9. There is visible the lossy polarization in Fig. 6 and Fig. 7, which has resulted in maxima (peak) shown in Fig. 7. The decrease of dissipation factor which follows mentioned maximum results in increase of the magnitude of polarization index at the temperature about 100 °C.

III. Conclusion

Finally, as a result of the experimental measurements, it can be stated that impregnants based on unsaturated polyesterimide resin dissolved in 1,6-hexanediol diacrylate (samples No. 3) have shown better resistance to the influence of water compared to samples No. 1 and No. 2 based on unsaturated polyesterimide resin with reactive monomer of the 1,4-butanediol dimethacrylate type. This statement is also supported by the results of the dielectric properties of that sample. Dissipation factor is lower and resistance in the case of sample No. 3 is higher than those of two other measured samples No.1 and No. 2, while permittivity is of the similar magnitude. It is expected without any doubt that the water will negatively influence the insulation properties of prepared samples but better resistibility in the case of sample No. 3 is demonstrated by the smallest change in the measured dielectric properties. On the contrary, the biggest change of the investigated properties occurred in samples No. 2, even in comparison with samples No. 1. Since the main difference between samples No. 1 and No. 2 is the addition of anti-corrosion protection and nanofiller, we consider this fact to be a highly probable reason for the deterioration of the measured properties exposed to the influence of water.

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