Improving the efficiency of power transformers insulation by modifying the dielectric paper with bacterial cellulose

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Abstract. The electrophysical characteristics of experimental types of electrical insulating paper modified by bacterial cellulose made of nano-gel film *Komagataeibacter xylinus*, disintegrated in various ways, were studied. The advantage of composites over traditional electrical insulating paper made of pine cellulose is shown in terms of electrical and mechanical strength, sorption activity and heat resistance. The efficiency of using an industrial blender to grind bacterial cellulose has been confirmed, which significantly reduces the time of its high-quality grinding.

1. Introduction

Plant cellulose (PCel) is the main renewable resource for paper, which is a component of high-voltage insulation. Practical experience of wide application of this dielectric indicates both its demand and insufficient knowledge [1-3]. The well-known unique properties, which include the immutability of the main dielectric characteristics during operation, are combined with serious disadvantages: low heat resistance and the need to use electrical insulating paper (EIP) in the impregnated state in order to increase electrical strength. However, despite these shortcomings, paper-impregnated insulation (PII) remains the basis type of insulation of power transformers (PT), which is an essential element of all energy systems. The service life of paper-impregnated insulation, as well as to a large extent of the power transformer as a whole, is determined by the electrical insulation paper. Therefore, for applied purposes it is necessary to work on improving the characteristics of EIP. These works include the modification of the base of the material made of insulating cellulose (ICel) pine structure by forming components [4-6], among which a special place is occupied by the thinnest fiber of bacterial cellulose (BC) with average diameter of fibrils 5.6 nm, in particular, obtained by disintegrating of nano-gel film *Komagataeibacter xylinus* (NGF CKX) [1, 4, 5]. Bacterial cellulose has affinity to the plant cellulose and the increasing prospects of its application [7, 8]. However, it is difficult to obtain a composite from EIP and BC using the traditional method of disintegrating the components with the help of the Valley roll due to the morphological features of the biopolymer. The present study is devoted to the search of ways to solve this urgent problem without reducing of the most important characteristics of a promising composite.
2. Methods

Laboratory castings of composite electrical insulating paper with the following composition were studied: 92.5% of pine cellulose sulfate processing with the addition of 7.5% of bacterial cellulose CKX (samples No. 1 – No. 3, figures 1 – 3). Nano-gel film of biopolymer was disintegrated in 3 different ways. For comparison (as a reference) the non-modified laboratory EIP made of 100% electrical ICel was investigated also (sample No. 4, figure 4).

![Figure 1. Sample No. 1 - composite, grinding of EIC and CKX in the Valley roll (in accordance with the patent [7])](image1)

![Figure 2. Sample No. 2 - composite, overdrive mode grinding of EIC and CKX in the Valley roll](image2)

![Figure 3. Sample No3 - composite: EIC - grinding in the Valley roll, CKX - grinding in blender JTC OmniBlend model TM-767](image3)

![Figure 4. Sample No. 4 – EIP of traditional manufacturing of 100% of EIC, grinding in the Valley roll](image4)

Using the laboratory installation to measure the breakdown voltage, a comparative assessment of the short-term electrical strength of the studied types of paper ($E_b$) in the initial state and after 100 hours of thermal aging in dry air at the temperature of 140° C was carried out. This temperature allows us to quickly age the EIP, but the physical and chemical processes that occur correspond to natural aging. In the process of thermal aging of samples No. 1 – No. 4 at the above conditions for 400 hours, the limit of their mechanical tensile strength was also measured using the test machine series ES model ESM301 "MARK-10". More detailed information about the measurement technique, methods of sample preparation and the standards used are given in [9-12].

The sorption activity of the studied types of paper in relation to the degradation products (enhanced copper catalyst) of petroleum transformer oil of the GK brand was determined by comparing the values of the relative light transmission coefficients ($K_{rt}$) of oil samples in the initial state and after thermal aging (at the temperature of 140 °C) in contact with the catalyst and paper, as well as without
it. Measurement of the $K_{rt\ 458}$ (at the wavelength of 458 nm) of samples of the dielectric fluids was made using microcalorimeter MKMF-1. Chemically pure glycerin was used as a standard of light transmission in the visible wavelength range.

The paper structure was investigated by scanning electron microscope (SEM) "Supra 55VP-25-78".

3. Results

Laboratory castings of composite electrical insulating paper with the following composition were studied: 92.5% of pine cellulose sulfate processing with the addition of 7.5% of bacterial cellulose CKX (samples No. 1 – No. 3, figures 1 – 3). Nano-gel film of biopolymer was disintegrated in 3 different ways. For comparison (as a reference) the non-modified laboratory EIP made of 100% electrical ICel was investigated also (sample No. 4, figure 4). The average values of the $E_b$ for 10 measurements of the EIP samples in the initial state and after thermal aging in the air are given in the table 1.

| Sample number | No. 1 | No. 2 | No. 3 | No. 4 |
|---------------|-------|-------|-------|-------|
| $E_b$ (kV/mm) before thermal aging | 9.5   | 10.6  | 11.3  | 6.2   |
| $E_b$ (kV/mm) after aging (100 h)  | 9.9   | 10.3  | 12.4  | 6.0   |

It is established that prolonged exposure to high temperatures did not lead to a significant change in the electric strength of the composites (No. 1 – No. 3), as is typical for monopaper (No. 4). This effect can be explained by the fact that the development of the breakdown channel occurs mainly on air inclusions. However, the values of $E_b$ samples with modified cellulose structure (No. 1 – No. 3) are at least 1.5 times higher compared to electrical insulation paper made of 100 % ICel of pine.

![Figure 5](image-url)  
**Figure 5.** Dependences of the tensile strength ($\sigma_p$) on the time (t) of thermal aging: 1 – sample No. 1, 2 – No. 2, 3 – No. 3, 4 – No. 4.

The obtained dependences of the average values of the limit of mechanical tensile strength ($\sigma_p$) on the time thermal aging (at temperature 140 °C) of the cellulosic materials is presented in the figure 5. At the first stage of aging, the strength of all types of EIP increases, which can be explained by a well-known fact: in the process of heat exposure, water is removed from the cellulose base and additional hydrogen bonds are formed. With further thermal exposure the value of $\sigma_p$ decreases with the development of thermo-oxidative destruction. However, throughout the tests, the values of this
characteristic of composites (No. 1 – No. 3) were significantly higher than one for the paper of traditional manufacture (sample No. 4). The dependencies are shown in the figure 5 allow us to assert that the modification of the web of EIP of plant cellulose with a biopolymer, the CKX contributes to improving the thermal stability of cellulose dielectrics.

Thus, the introduction of CKX into the paper pulp contributes to the improvement of the most important indicators of EIP as a dielectric material. As a result of tests it is established that the greatest positive effect is observed at disintegration of bacterial cellulose by the blender (sample No. 3). The specified compound has also elevated sorption activity in comparison with all investigated types of EIP. Measurements showed that, indeed, after 200 hours of thermal exposure (at 140 °C), the value of the coefficient $K_{rt\ 458}$ was 60% for the sample of oil "GK", which was artificially aged in contact with the copper catalyst and the sample of the paper No. 3. For the remaining oil samples, the coefficient $K_{rt\ 458}$ was in the range of 41 – 55 % for both monopaper (sample No. 4) and composites (samples No. 1 and No. 2). Indeed, the coefficient $K_{rt\ 458}$ of the oil, which was exposed to aging in contact with the catalyst, but without paper, at the same aging time (200 hours), was equal to 14 % only.

4. Conclusion
The main result of the study can be considered to obtain additional information indicating the feasibility of modifying the insulating paper with a CKX biopolymer, as well as confirmation of not only the possibility but also the effectiveness of disintegrating bacterial cellulose with an industrial blender in order to accelerate the process of grinding of the biopolymer, without damaging its structure, as noted in our publication [4]. Further development of work in this direction can improve the resource and efficiency of paper-impregnated insulation of power transformers.

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