DETERMINATION OF WATER NANODROPS IN OIL IMPREGNATED ELECTROTECHNICAL PRESSBOARD

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Abstract - The paper presents an analysis of experimental and theoretical relationships of AC conductivity in composite cellulose - mineral oil - water nanodrops, with use of quantum mechanics. It was found that in the structure of oil impregnated pressboard, moisture is in the form of nanodrops. The average size of the nanodrop is approximately 3.18 nm and contains about 200 molecules of water on average.

Keywords - Electrotechnicalpressboard, mineraloil, waternanodrops, AC conductivity

I. INTRODUCTION

Cellulose in form of paper and electrotechnical press board impregnated with insulativoil, for about 100 yearsis a mainly used material for the production of high-voltagepowertransformersinsulation.
Duringlong-term use, moisturecontent in paper-oilinsulation gradually increases. This significantly reduces the quality of paper and oilinsulation, the reliability of the transformers, and in many cases can cause failure and high economiclosses.

From the point of view of power transformers safety, itisimportant to develop methods of determining the moisturecontent of celluloseinsulation.

Determination of moisturecontent in solid insulation of powertrans for mersis most oftendone by non-destructive methods, primarily - electricones, based on the analysis of relaxationprocesses. These methods belong to two basicgroups - time-related measurements such as RVM (Return Voltage Measurement) [1,2] and PDC (Polarization Depolarization Current) [2] methods, and measurements in the frequencydomain FDS (FrequencyDomainSpectroscopy) [3].

In paper [5], based on the conductivity measurment made by PDC metchod, it was estabiched, that conduction of dampened oilimpregnated pressboar discosed by the electron exchange (tunneling) and is determined by the presence of watermolecules.The purpose of the aricleis to analyze the experimental and theoretical relationships of AC conductivity of compositecellulose- mineraloil - waternanodrops, with the use of quantum mechanics elements and to determine on thisbasis the averagedimensions of waternanodrop in compositecellulose - mineraloil.

II. RESULTS AND DISCUSSION

According to the work [6], in case of electrontunneling between the nearest potential wells, thereis a verystrong (exponential) dependence of potentials wells concentrationN_0 on the conductivity. In thiscase, dependence, given in article [7], was used to analyze the temperature and concentration of the potentialwellsdependence on the conductivity:

$$\sigma(r, T = const) = \sigma_0 \exp\left(-\frac{\beta \cdot r}{R_0} - \frac{\Delta W}{k \cdot T}\right) \quad (1)$$

Where:r is the average distance between potential wells; R_0 is a position radius of a wave function of a hopping electron; b is a numeric factor ranging (1.75 ± 0.05)[6]; ΔW - activation energy of conductivity, k - Boltzman constant.

In paper [5] it was assumed that wells of potential are randomly arranged single molecules of water. The average distance between them r_1 is given by formula (2):

$$r \cong N_0^{-\frac{1}{3}} = \left(\frac{X \cdot \rho}{100 \cdot u \cdot M_{H_2O}}\right)^{-\frac{1}{3}} \quad (2)$$

where q = 1,000 kg/m3 is the pressboard density;
M_{H2O} = 18 is the water molecular mass; u = 1.67 10^{-27} kg is the atomic mass unit; and X is the moisture.wt%.

In the work [8], it has been found that activation energy of the AC conductivity from formula (1) is relatively independent of the moisture content and is equal $\Delta W \approx$ (0.9138 ± 0.05519) eV. Using the empirically determined independence of activation energy from the moisture content (distance between water molecules) the formula (1) can be transformed for the case T = const. to:

$$\log \sigma(r_1) = \left[\log \sigma_0 - \frac{\Delta W}{kT}\right] - \frac{\beta}{R_0} r_1 = \quad (3)$$
$$= -\frac{\beta}{R_0} r_1 + C$$

Where: $C = \left[\log \sigma_0 - \frac{\Delta W}{kT} \right]$

Figure 1 shows the relationship of AC conductivity, measured at frequencies 10-4 Hz, 10-3 Hz, and 10-2 Hz in function of the distance between molecules of water, calculated from formula (2). Measurement temperature was 20 °C. As can be seen in Figure 1, the resulting dependencies are linearly decreasing relationships, which is consistent with equation (3).

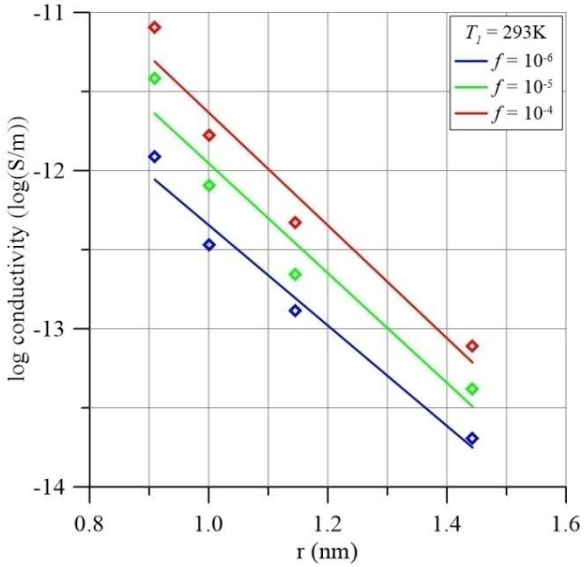


Figure 1. Measurement results of pressboard containing water moleculesAC conductivity versus the distance between water molecules calculated from formula (2)

In order to determine the dimensions of water nanodrops, elements of quantum mechanicswere used. The following assumptions[9]have been established.

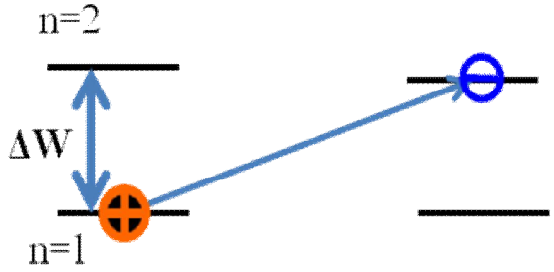


Figure 2. Basic state (n = 1) and first unoccupied state (n =2) between which the electron jumps from one neutral well to the other.

Electron is tunneling from the neutral water molecule, which is located in the nanodrop. Tunneling is done from the basic state to the first unoccupied statelocatedabove (Figure 2).Since the valence electron of the water molecule is heavily shielded from the nucleus through lower located electrons, its first ionization energy is about 12.6 eV [10-13] and is very close to the hydrogen ionization energy of 13.595 eV. The difference between these values is only 7.3%. So close ionization energy values for the water molecules and hydrogen atom, means that the structure of energetic states of water molecule valence electron is very close to the structure of hydrogen atom states.

In order to calculate the energy difference between the basic state and the first unoccupied state in water molecule, we apply the Bohr's formula for the energy between states in the hydrogen atom [14]:

$$h\nu_{j,k} = E_j - E_k = \frac{m_e \cdot e^4}{8 \cdot \varepsilon_0^2 \cdot \varepsilon_r^2 \cdot h^2} \left(\frac{1}{j^2} - \frac{1}{k^2} \right) \quad (4)$$

Dielectric permeability of insulative oil impregnated pressboard is $\varepsilon_r \neq 1$. Hence, in formula (4), the square of relative permeability is found in denominator.

In formula (4) we assume that the valence electron of the water molecule is in the prime state with the principal quantum number j = 1. In formula (4), in case of tunneling to the first unoccupied state k = 2.

By substituting j = 1, k = 2 and activation energy of the DC conductivity $\Delta W = h\nu$ to formula (4), we can calculate the relative dielectric permeability in the surrounding of water molecule, to which electron is tunelling.

$$\varepsilon_r = \sqrt{\frac{3 \cdot m_e \cdot e^4}{32 \cdot \varepsilon_0^2 \cdot \Delta W \cdot h^2}} \quad (5)$$

By substituting the formula (5) with the activation energy of the conductivity and the known constants - *m*, *e*, ε_0, *h* we obtain the relative permittivity of the insulating material in the surrounding of nanoparticle of water to which the electron is tuneled. Its value is $\varepsilon_r \approx 4{,}98$.

Radius of the first Bohr's orbit (n = 1) for hydrogen atom in vacuum, according to formula (6) is 0.0529 nm and is denoted by the formula:

$$R_n = \frac{\varepsilon_0^2 n^2 h^2}{\pi e^2 m_e} \quad (6)$$

When we place the nanoparticle of water from which electron jumps, into pressboard impregnated with insulating oil, with relative permeability $\varepsilon_r \approx 4{,}98$, the Bohr's radius entering the equation for the conductivity (1) will increase (ε_r) 2 times and its value will be $R_0 \approx$ 1,312 nm. Experimentally determined from Figure 1, the value of the direction coefficient, entering formula (3), calculated from the assumption that the moisture in the pressboard is in the form of single water molecule, is 7.806 and is described by the formula::

$$\left(\frac{\beta}{R_0} \right)_{EXP} \cdot r_1 = 7{,}806 \cdot r_1 \quad (7)$$

Where: β≈ (1.75 ± 0.05) [1], r_1 - the distance between individual molecules of water.

Given the fact that water is in nanodrop form, the distance to which the electron is tunneled is different from r_1. We will mark it r_n. By substituting R_0≈1,312 nm to the formula (7) above, we should increase the distance at which the electron jumps to r_n. Substituting the formula (7) with the values β and R_0≈1,312 nm, calculated from the Bohr 's model, we obtain:

$$\left(\frac{\beta}{R_0}\right)_{BOHR} \cdot r_n = 1{,}34 \cdot r_n \quad (8)$$

By comparing the experimental value (7) and the calculated with Bohr's model (8), we come to the conclusion that the distance between the molecule from which the electron jumps and the molecule to which it jumps should be much higher than if the water was in the form of single molecules. This means that the water molecules are in the form of nanodrops, each of which contains an average of *n* water molecules. The average distance between water nanoparticles will increase in this case.

$$\frac{r_n}{r_1} = \frac{\left(\frac{\beta}{R_0}\right)_{EXP}}{\left(\frac{\beta}{R_0}\right)_{BOHR}} = 5{,}82 times \quad (9)$$

Assuming that water molecules accumulate in a pressboard impregnated with insulating oil in the form of nanodrops, and each nanodrop contains an average of n molecules of water, the formula for r_n should be written as:

$$r_n = \left(\frac{X \cdot \rho}{100 \cdot u \cdot n \cdot M_{H_2O}}\right)^{-\frac{1}{3}} \quad (10)$$

By substituting the formulas (2) and (10) we obtain:

$$\frac{r_n}{r_1} \cong (n)^{1/3} \quad (11)$$

From formula (11) it follows that:

$$n = \left(\frac{r_n}{r_1}\right)^3 \quad (12)$$

By substituting formula (12) to formula (9), we obtain that water nanoparticles contain approximately 200 molecules of water on average. The mass of such nanodrop is:

$$m_n = n \cdot M_{H_2O} \cdot u \quad (13)$$

Nanodrop volume:

$$V_n = \frac{m_n}{\rho} = \frac{n \cdot M_{H_2O} \cdot u}{\rho} = \frac{\pi \cdot d^3}{6} \quad (14)$$

Formula (14) shows that the diameter of water nanodrop containing n molecules is:

$$d = \sqrt[3]{\frac{6 \cdot n \cdot M_{H_2O} \cdot u}{\pi \cdot \rho}} \quad (15)$$

By substituting for the formula (15) the constants and the number of water molecules in nanodrop n≈200, we obtain that the diameter of the nanodrop is d = 2.26 nm.

CONCLUSIONS

Based on the elements of quantum mechanics, obtained experimental and theoretical relationships of the AC conductivity of composite cellulose - mineral oil - water nanoparticles, were analyzed.It was found that in the structure of oil impregnated pressboard, the moisture is in the form of nanodrops.The nanodrop contains an average of about 200 water molecules and its average diameteris about 3.18 nm..

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