Features of electroosmosis usage for drying and moisture protection of electrical equipment

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Abstract. The article describes a new method for drying electric motors and transformers based on electrokinetic phenomenon of electroosmosis. The process of electroosmotic motion of moisture in insulation capillaries is described. The advantages of electroosmotic drying associated with a significant reduction in energy and labor costs are presented.

1 Introduction

One of the problems arising during operation of electrical equipment in Russia and other countries is wetting of winding insulation. The annual number of failures of electric motors (EM) due to wetting of windings insulation in the agricultural sector and some other industries reaches 20-30% [1, 2].

The development of specialized EM for wet environment of agricultural premises and mines carried hope for the possibility of solving the problems of insulation wetting. However, the experience in operating such EMs has cast doubt on their ability to withstand long-term exposure to a humid environment. The idea of sealing EM enclosures of special designs could not be fully realized. Rubber gaskets and seals at places where the shaft goes out of the housing were not able to provide sealing at change of temperature regime. The engine "breathed" and moist air was sucked in. When a winding cooled down, the moisture condensed, which caused hydrolysis and reduction of the insulation resistance R [3, 4]. Calculations showed that in EM of a 160 kW capacity and a cavity volume of 0.05 m^3, 1.4 g of moisture accumulate during one day of inactivity [5]. So, the EM insulation R in short-term operating conditions in an environment with 100% air humidity decreased to 100 kOhm [6].

A similar situation is typical for transformers [7, 8], although the number of failures is less, but it is considerable, especially in terms of economic damage. So, according to William Bartley, the head of the working group for damage analysis of power transformers of the International Association of Engineering Insurers (IMIA), the damage caused by failure of only one transformer due to insulation wetting amounted to $ 175,000 [9]. The main source of transformer wetting is atmospheric moisture penetrating under the influence of pressure gradient, especially through weakened seals. According to Vanina B.V. damage to power transformers with voltage of 110-500 kV in operation over a period of 12-25 years is largely due to wetting of windings, as well as penetration of atmospheric moisture through high-voltage bushings (130 cases) [10].

There are quite a few ways to dry EM, but all of them are limited to thermal ones: electric lamps, ovens, blowers, welding transformers, etc. [6, 3]. Transformers are also dried mainly by thermal methods: induction heating, short circuit current, direct current, zero sequence current, circulating hot oil, heating the tank with infrared radiation, blowing by hot air, in a drying chamber, etc.

Thermal drying methods for EM and transformers can cause warping, thermal degradation, local overheating and thermal aging of insulation. These methods are often associated with disassembling and dismantling of EM and transformers from their workplaces, as well as with a presence of special equipment and increased energy consumption [11, 12].

The known methods of moisture protection are mostly thermal. They are associated with energy consumption and heating of windings of electrical equipment (EE). Moisture protection can be implemented by sealing (encapsulation) of EE windings [3]. However, in the first case there are drawbacks inherent to EOD. In the second case, complete sealing, as a rule, cannot be achieved and the windings continue to become wet.

At the Department of Electrical Equipment of the Vologda State University, new methods of drying and moisture protection of EE have been developed, based on the electrokinetic phenomenon of electroosmosis [13-20].

Electroosmosis was discovered in 1809 by F.F. Reuss and consists in motion of liquid in capillary systems induced by electric field. Modern concept of electroosmosis mechanism is based on the idea of the existence of a double electric layer (DEL) at the interface between liquid and solid phases. A phase with higher dielectric constant (water) is charged positively, and with lower one (dielectric) is charged negatively. Due to extremely high dielectric constant of water, a wide variety of dielectrics get a negative charge in it. The reason for DEL formation may be different. At the interface between two phases, there is a possibility for absorption of ions from the surrounding solution, which are formed there due to electrolytic dissociation. According to another theory, at a certain temperature in the ionic lattice on the surface and inside the solid phase of dielectric, there are some free places. The charge will be negative if the cation vacancies are in excess, and positive if there is an excess of anion vacancies.

The physics of DEL is shown most consistently in [21]. DEL at the dielectric-liquid interface is represented as two parallel surfaces (Fig. 1), where the dielectric surface is negatively charged, and the dense layer of counterions of liquid phase has a positive charge.

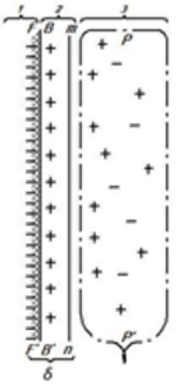

Fig. 1. Structure of a double electric layer [21]: *BB*` is the dense layer of counterions; *FF*` is the dielectric surface; *mn* is the sliding surface of the diffusion part of liquid; *PP*` is the diffusion layer of counterions; 1 is the solid phase; 2 is the adsorption (fixed) liquid layer of thickness δ; 3 is the moving liquid layer.

Counterions in liquid phase are under the influence of two mutually opposite forces. On one hand, they are electrostatically attracted by dielectric surface, on the other hand, the thermal motion of liquid particles, in which counterions also participate, tends to uniformly disperse them in the thickness of liquid. As a result of interaction of these oppositely directed forces, the counterions in liquid form a diffuse ionic atmosphere near the solid surface of adsorbent. Concentration of counterions is greatest near the surface *FF*`, and then gradually decreases. If liquid adjacent to the solid surface *FF*` is divided into a series of thin layers f_1K_1, f_2K_2, f_3K_3, then each of them will be charged with counterions to a potential, which decreases when this layer is moved from the solid wall (FC curve in Fig. 2). The line CQ indicates the boundary of the diffuse layer, and the distance F`C corresponds to its thickness.

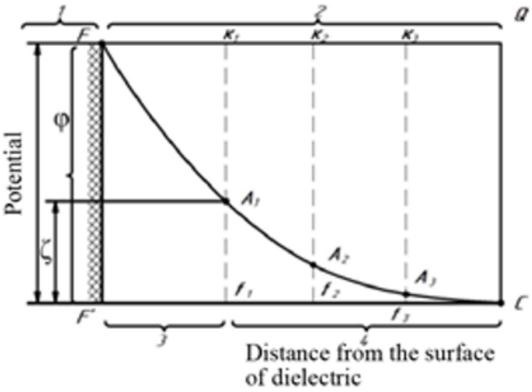

Fig. 2. Potential distribution in the double electric layer and in the diffuse part of liquid [21]: CQ is the boundary of diffuse layer of counterions; 1 - solid phase (dielectric); 2 - liquid phase (water); 3 - adsorption layer; 4 - moving liquid layer.

When liquid moves along a solid surface, liquid phase slides not along the boundary between the solid surface and liquid, but along another surface, slightly shifted toward the liquid phase (surface *mn* in Fig. 1). The thinnest adsorption layer of liquid *B`Bmn* directly adheres to the solid surface *FF*` and is held by it very firmly. During general liquid motion, this layer and the counterions inside it (“bounded” counterions) remain motionless. Only counterions that are behind the sliding surface *mn* (“free” counterions) can flow out together with liquid. The fixed adsorption layer *B`Bmn* contains only a certain part of counterions. This part only lowers the potential of dielectric solid surface, but does not completely compensate its charge. In this case, as a result of interaction between positive and negative charges in a fixed layer of thickness δ, some potential that is a fraction of total potential of a solid surface remains not neutralized. Thus, at the boundary *mn* (Fig. 1), i.e. on the sliding surface, a special difference (jump) in potentials is created, which is called the electrokinetic or zeta potential ζ. The ζ potential is equal to the potential difference between the solid surface together with adsorption layer of liquid on one hand, and its moving part on the other. Total drop of potential from its value on the surface *FF*` to zero at point *C* corresponds to the maximum potential difference between the solid wall of dielectric and all counterions (Fig. 2) .This maximum potential difference is s thermodynamic potential φ, but the electrokinetic potential ζ plays a major role in the electrokinetic phenomena.

When electric field is applied to a capillary with liquid, the excess ions of the same sign in the outer DEL part begin to move to the oppositely charged pole (Fig. 3, a). Ions of the inner part of DEL, located directly on the solid wall, and ions of the opposite sign in the adsorption layer do not participate in liquid motion. In the middle part of the capillary far from the wall, there are equal numbers of ions of both signs.

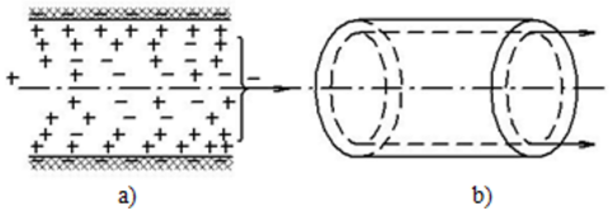

Fig. 3. Capillary model of electroosmosis: a) charge structure; a) motion of a liquid volume.

Therefore, in electric field ions of different signs move in opposite directions with velocities corresponding to their mobilities and potential gradient. H^+ cations are more mobile than hydroxyl groups of OH^- anions; therefore, the motion of ions in aqueous medium occurs mainly from the positive to the negative pole. Thus, a directed flow of excess ions of diffuse layer is created near the wall. In a round-shaped capillary, such an ion flow has a cylindrical shape and moves to the oppositely charged pole (Fig. 3, b). During its motion, the flow carries away the rest mass of liquid in the capillary, which is facilitated by friction and molecular cohesion.

Note that the latter circumstance is most significant when water is removed from the capillary, because water weakly dissociates into ions and dehydration only due to motion of ions is insignificant. At the same time, the described representation of electroosmotic liquid transfer indicates that the more ions of the same sign are in the diffuse part of DEL, i.e. the larger ζ is, the stronger is the resulting action of the moving near-wall layer of ions and the faster the entire liquid mass in the capillary should move.

If the potential difference U is applied to the capillary ends, and electric field strength is parallel to the axis of the capillary tube, then the electric force acting on the surface unit of the charged layer (cylinder) of liquid can be determined as:

$$F = \frac{\varepsilon\zeta U}{4\pi\delta l}, \qquad (1)$$

where l is the capillary length;

δ is the thickness of liquid adsorption layer;

ε is the dielectric constant of liquid.

The moisture transfer mechanism in a single direct circular capillary in Fig. 3 can be transferred to any heterocapillary system, which consists of capillaries of various sections and directions. The materials used to insulate EE windings are capillary systems. The pores and capillaries that are found in electrical insulating materials (EIM) can be of a variety of shapes and sizes, open-type and blind. They can connect to the environment directly or using a branched system. According to the classification of Rebinder P.A. [22], the forms of moisture connection with material are divided into three groups: chemical, physico-chemical, physico-mechanical. Of these, only the third form of connection is exposed to electroosmosis. Thus, under the influence of electric field at EOD, all moisture from EIM cannot be removed. But on the other hand, water is displaced, that is in the most dangerous condition for electrical properties of insulation.

Moisture from windings can be removed by applying a potential difference between the current-carrying parts and the housing, i.e. by creating electric field in insulation, which causes electroosmotic motion of water towards the negative electrode. As a rule, EM windings are connected into a star, positive potential is applied to them, and negative potential is applied to the housing [11, 12]. Under such connection of the electroosmotric drying device (EOD), the sequence of moisture motion in slot insulation is shown in Fig. 4.

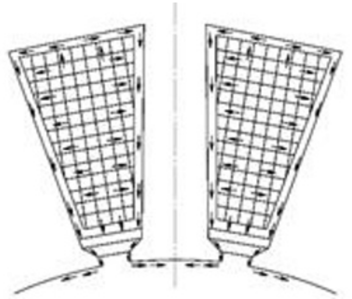

Fig. 4. Geometrical model of electroosmosis for EM slot insulation (arrows indicate the motion of moisture at EOD).

Here, a cross section of two stator slots is shown, made along a layer that insulates the individual plates of the magnetic circuit. The arrows indicate the direction of moisture motion. Moisture from the slot parts of insulation is displaced to the slot walls. Further, under the influence of excess pressure moisture is displaced into the stator cavity through the slots and the end parts of the slots. Our calculations show that this excess pressure in EOD process is six times greater than the atmospheric one. Moisture is removed from inter-turn parts of insulation, under the action of diffusion gradient. From the interphase parts of insulation that are not directly exposed to electric field during EOD according to the “star-housing” scheme [20], water moves to the slot parts also under the action of diffusion gradient and the process is repeated. When EM is turned on and heated, moisture evaporates into the environment.

EOD does not heat the insulation, drying is cold, and energy consumption is 2-3 orders of magnitude lower than during traditional methods of EE thermal drying. During EOD there is no need to disassemble EE or to dismantle it from its workplace, which reduces labor costs by 2-3 times [11].

Electroosmotic moisture protection (EOMP) is based on electroosmosis like EOD, but it is used more rarely than thermal methods of moisture protection. When potential is applied to the winding of inactive EM relative to the housing, electric field is created in the insulation system, which prevents moisture penetration into the winding, thus a preventive moisture support is implemented [11]. EOMP has all the advantages typical for EOD.

The process of EOD and EOMP for transformers is more complicated than that for EM because of complexity of electrical insulation design, the presence of oil and the lack of close contact of insulation between the winding conductors and the housing [19]. Potential difference from EOD and EOMP devices is supplied on the winding conductors and the transformer housing. Therefore, EOD and EOMP for transformers require special consideration [23].

2 Conclusions

1. The electrokinetic phenomenon of electroosmosis is applicable for drying and moisture protection of insulation of EE windings.

2. The use of EOD does not reduce the service life and the resource of EE electrical insulation, which is typical for thermal drying methods.

3. The EOD is cold, does not require disassembling and dismantling of EE from its workplace. It requires minimal energy and labor consumption in comparison with thermal drying methods.

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