Improving the efficiency of electroosmotic drying of electric motors insulation

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Abstract. The actual problem of electric motors (EM) operation associated with wetting of windings insulation is considered. A new method of EM drying based on electrokinetic phenomenon of electroosmosis was developed at the Department of Electrical Equipment of Vologda State University. It was shown that water molecules can take part in formation of non-mobile hydrated positively charged hydrogen ions. In this case, hydrogen ions become bound, lose their mobility and ability to take part in the process of electroosmotic drying (EOD). EOD efficiency is drastically reduced. It was proved that it is possible to prevent ion hydration, increase their mobility, penetration ability and, thereby, increase the EOD efficiency by applying a pulsed voltage component to the EOD process with a duty factor of 4. As a result, a new EOD method was developed using a pulsed voltage component that increases the speed of EM insulation drying by three times.

1 Introduction

The number of failures of electric motors (EM) associated with wetting of windings insulation reaches 20-30% [1-3]. The environment of livestock complexes in agro-industrial production and at some industrial enterprises contains hydrogen sulfide, carbon dioxide, ammonia, etc. These gases, when combined with water vapour, form acids and alkalis, which bypass the EM insulation system and sharply reduce the resistance [4].

Moisture exposure to electrical insulation materials of EM insulation system result in hydrolysis of EM insulation, appearance of molds [5,6], deterioration of all electrical characteristics.

The appearance of coil faults in mesh EM winding takes place not only due to switching overvoltages when EM is turned on or its vibration during operation. The reason may be a winding break due to formation of galvanic pair in acidic compounds of moist aggressive environment.

A known effect is "steaming" wet insulation of EM when it is switched on [7]. In this case, the insulation resistance R sharply decreases and the probability of breakdown increases.

Thus, EM maintenance in a humid environment is complicated by the need for regular drying. Almost all known drying methods are thermal [7,8].

Any thermal drying method, to one degree or another, harms the EM insulation and reduces its "life". It is explained by warping, increased cracking, shrinkage, mechanical stress, destruction of molecular structures and thermal aging of insulation. Thermal

drying methods are inconvenient, require dismantling and disassembly of EM, increased energy consumption and do not contribute to lower production costs [3, 9-11].

A new method of EM drying was developed, based on electrokinetic phenomena, one of which is electroosmosis [3,4,6]. Moisture is removed from the capillary EM insulation system using electric field [12] and a special electroosmotic drying device (DEOD) [3].

The main advantages of electroosmotic drying (EOD) are that it flows without increasing the EM insulation temperature. The energy consumption during EOD for drying EM with a power of 5 kW is incomparably lower than with thermal methods and amounts to 30-40 W·h. Moreover, EM does not need to be disassembled, which increases labour productivity, since it reduces labour costs by 2-3 times [3]. However, EOD applying is faced with the problem of reducing its duration and increasing efficiency.

The purpose of this study is to increase the efficiency of EM EOD by combining constant and pulsed electric fields.

2 Methodology foundations of research

Water is a strongly polar dielectric. Perfectly pure water weakly dissociates into H^+ , OH^- ions; therefore, its electrical conductivity is insignificant and amounts to only $3.8 \cdot 10^{-10}$ Ohm·m. Figure 1 shows a scheme of dissociation of water molecule into ions.

Fig. 1. A scheme of dissociation of water molecule with formation of ion complexes.

The theory of electrolytic dissociation explains the appearance of hydrated ions (ionic complexes), which are unstable compounds of water molecules (clusters). The existence of hydrated ions is proven. For example, a hydrogen ion always binds in solution with a single water molecule, forming a hydroxonium ion H_3O^+ . H^+ ions with high penetration ability and mobility are the main driving force for fluid transfer during EOD. At the same time, there are few free H^+ ions in liquid, and for efficient EOD process its amount should be as great as possible [13].

The electrical model of EM insulation during EOD can be represented by an insulation equivalent circuit, by adding resistance R_e to electroosmosis current i_e and EMC of the double electric layer E_d (Fig.2). Connecting DEOD to the circuit induces currents i_∞ , i_a , i_R , i_e .

Fig. 2. Electrical insulation model for EOD: C is the geometric capacitance; R is the resistance of through and surface conductivities; r is the active losses associated with polarization of dielectric; C_a is the absorption capacity; R_e is the resistance to electroosmosis current; i_∞ , i_a , i_R , i_e are currents of geometric capacitance, through and surface conductivities, absorption, electroosmosis; E_d is the EMC of the double electric layer; A is the EOD device.

Currents of geometric capacitance i_∞ and absorption i_a do not have a drastic influence on EOD process, since they quickly decrease to insignificant values. For current i_e in the capillary of EM insulation one has:

$$i_e = \frac{\Delta P \epsilon R^2 \xi}{4 \mu l}, \quad (1)$$

where ΔP is the pressure difference at the capillary ends;

R is the capillary radius;

ϵ is the dielectric constant of water;

μ is the dynamic viscosity coefficient of water;

l is the capillary length;

ξ is the electrokinetic potential (zeta potential).

In expression (1) $\Delta P \sim U$, where U is the voltage at the output terminals of DEOD, $E_d \sim \xi$. i_e is induced by motion of water ions, which carry neutral H_2O molecules with them. As a result, an increase in i_e increases the EOD efficiency. Analysis of formula (1) shows that it is possible to actually increase i_e by acting on μ , U , ξ . This

leads to the development of various ways to improve the EOD efficiency.

For through conductivity current i_R one can obtain [7]:

$$i_R = \frac{\pi R^2 \gamma U}{l^2}, \quad (2)$$

where γ is the specific electric conductivity of liquid.

The i_R current does not have a beneficial effect on the process of insulation dehydration. i_R shunts the electrodes and causes a decrease in DEOD output voltage, and hence the EOD efficiency. Thus, one must strive to reduce i_R . The surface conductivity current i_s caused by pollution and surface wetting of insulation is added to current i_R ; therefore, for an effective EOD process, a clean and dry insulation surface is needed [7].

The criterion for EOD efficiency can be its duration τ . The faster drying takes place, the higher its efficiency is subject to other conditions (energy saving, low labour costs, etc.).

In [7], an engineering formula was obtained for determining the EOD duration as a function of initial R_1 and final R_2 insulation resistances, voltage at DEOD output U , and overall EM dimensions:

$$\tau = \frac{\delta l h}{\alpha \lambda U [h + (k+1)l]} \ln \theta(R_1, R_2), \quad (3)$$

where l , h are half width and height of EM groove;

δ is width of EM insulation groove;

λ , α are coefficients of electroosmosis and diffusion;

k is electric field averaging coefficient during EOD.

It follows from (3) that it is possible to decrease τ and increase the efficiency of EOD process by increasing U , however, the DEOD voltage for EM 0.38; 6-10 kV is not recommended to increase beyond certain limits due to sharp increase in i_R according to (2) and the risk of insulation breakdown. In addition, an increase in i_R shunts the electrodes, which results in a decrease in DEOD output voltage, and, consequently, the EOD efficiency. Thus, the possibility of intensification the EOD process due to a simple increase in U is quickly exhausted and the search for other ways is necessary.

An increase in the number of free H^+ ions in liquid will make it possible to increase the zeta potential ξ and EMC E_d [13], which, according to expression (1) and fig. 1, increases current i_e . At the same time, the “harmful” current i_R somewhat increases, however, the positive effect of increasing i_e exceeds the negative impact of i_R growth on EOD efficiency. It is possible to increase the number of free H^+ ions by destroying the bound hydrated H^+ ions. An increase in the number of H^+ ions is equivalent to an increase in diffusion coefficient, which, according to (3), reduces τ .

The specifics of EM operating in agricultural and chemical industrial plants requires consideration of the influence of ammonia on the intensity of EOD process. Ammonia, combined with water, forms a hydrate of ammonium oxide NH_4OH :

NH_4^+ ions are also subject to hydration (fig. 3). The hydrated NH_4^+ ion not only becomes inactive, but also binds the neutral H_2O molecules. Thus, the EOD process in the ammonia medium slows down. Therefore, hydration of NH_4^+ ions must be prevented.

Fig. 3. Scheme of hydrated ammonia ions.

In this study, experimental samples were AIR EM of common industrial use with a power of 1.5 kW. Its insulation system includes Lavitern (groove box and groove wedge), film-asbestos millboard (interphase gaskets), PETV-2 (winding wire).

For statistical validity, three EMs were dried in each experiment (fig. 4). Drying was carried out by two DEOD devices developed at VoGU [3]. A constant voltage was generated at the output of the first DEOD. At the output of the second DEOD, a pulsed component was superimposed on DC voltage component, the parameters of which were determined from the expressions (4)-(12).

Fig. 4. Change in EM insulation resistance R during EOD by voltage of various shapes: 1 – Curve of EOD process when imposing a pulsed voltage component; 2 – The same during EOD under DC voltage.

The insulation resistance R was measured using the F4101 megaohmmeter. The positive pole from the DEOD output during drying was connected to EM windings connected to a star, and the negative pole to the casing. Preliminary humidification of EM windings was carried out in the KTV-0.4 moisture chamber at a temperature of $T = 20 \pm 2$ °C and a relative air humidity of $\omega = 97 \pm 3\%$ without moisture condensation for 96 hours. To speed up the humidification process, the EM bearing shields were removed.

3 Results and discussion

It is possible to increase the penetration ability, mobility of ions and water molecules, and prevent their hydration by applying an additional pulsed electric field to the insulation system during EOD. Thus, we have developed a new approach for EOD. The essence of the phenomenon is explained from the standpoint of theoretical electrochemistry. H^+ ion or a dipole molecule H_2O located in a liquid medium has shells consisting of molecules or ions (figs. 1,3,5). The motion of the central ion (fig.5) towards the corresponding electrode is associated with destruction of shell and formation of a new one.

Fig. 5. Graphical representation of H^+ ion in the ionic shell in electric field during EOD.

The Debye – Onsager theory [14] suggests that behind the ion (hydrogen or ammonia) there will always be some excess charge of the opposite sign, and the resulting electric forces of attraction will inhibit its motion. So, when a short-term electrical pulse is supplied with sufficient strength to the insulation system, at certain parameters of pulse, the central ion will detach from the shell, and the new one will not have time to form. As a result, a non-mobile cluster will be destroyed, and its individual components will be freed.

The mechanism of destruction of ionic complexes in figs. 1,3,5 can be explained from the standpoint of energy. The energy supplied to the pulse insulation must be sufficient to destroy the clusters. Clusters have their own internal energy. Formation of clusters is associated with absorption of energy from water system, and their destruction is associated with energy release. The ions and molecules that make up the cluster oscillate in some way relative to their average positions. The amplitude and frequency of their oscillations is also determined by the internal energy of cluster. If the energy of electrical pulse applied to insulation resonates with the cluster energy, then the amplitudes of vibrations of its constituent ions and molecules will be so strong that the cluster will decay. Insufficient or excess pulse energies may not cause resonance and destruction of clusters. Moreover, excess energy of electrical pulses can lead to heating of EM insulation and increased energy consumption during EOD process. The Wien effect, the Debye–Falkenhagen theory [14] suggest an increase in electrical conductivity of electrolyte solutions with increasing frequency of the applied electric field due to the destruction of ionic complexes and formation of free molecules and ions, and, therefore, confirm what was said.

Application of pulsed voltage (fig.6) at the DEOD output terminals contributes to the destruction of ionic complexes (clusters) in figs. 1,3,5.

Fig. 6. EOD voltage curve with constant and pulsed components: H, h are amplitudes of constant U- and pulsed U- voltages.

Pulsed voltage will also periodically weaken the level of space charge of the opposite sign at the electrodes, thereby weakening the electrode effect during EOD process. The positive electrode is the coil, and the negative is the EM housing. All this will positively affect the release of H^+ ions with high mobility. Motion of H^+ ions toward the EM shell will cause the motion of neutral water molecules due to its viscosity. Water will be displaced from the groove portion of EM insulation onto the surface of the stator iron and groove wedges. The insulation R will increase and after a while EM can be started. The work of EM will lead to its heating, evaporation of moisture from the surface of iron, grooved wedges and a further increase in insulation resistance.

When applying a pulsed component, it is prohibited to change the voltage polarity. Changing the electric field sign will lead to the transfer of H^+ ions in the opposite direction to the insulation of winding and EM will begin to moisten. To prevent the reverse transfer of moisture and re-wetting, the polarities of the constant and pulsed components of electric field must coincide.

In general, the optimum energy of voltage pulse during EOD process will be determined by a combination of parameters: shape, duty cycle, repetition rate, ratio of the amplitude of pulsed component to the maximum EOD voltage. Turning to the shape of pulse, we note that the steeper the front, the shorter the time for which a portion of energy is sent to the clusters. This facilitates the conditions for their decay. A rectangular pulse with a leading edge duration of $1 \mu s$ A is sufficiently steep and has a simplified engineering implementation in DEOD. The EM insulation system, as a DEOD load, has a predominantly capacitive nature. To reduce the distortion of waveform of DEOD output pulses one should not go beyond frequencies above 2000 Hz.

The expansion in a Fourier series of function that describes the change in voltage of EM insulation system during EOD process under the combined action of a constant and pulsed component has the form:

$$U(\tau) = H + \left(1 - \frac{A}{T}\right)h - \frac{h}{\pi} \sin \frac{2\pi}{T} A \cos \frac{2\pi}{T} t - \frac{h}{\pi} \left(1 - \cos \frac{2\pi}{T} A\right) \sin \frac{2\pi}{T} t + \dots = H + \left(1 - \frac{A}{T}\right)h + \frac{2h}{\pi} \sin \frac{\pi}{T} A \cos \left(\frac{2\pi}{T} t + \varphi\right) + \dots, \quad (4)$$

where H, h are shown in fig.5.

Taking into account (4) and expression (2.87) from [15], the mobility of water molecules during EOD for voltage curve, shown in fig.5, will be determined as follows:

$$U = \frac{\varepsilon \xi}{\mu} \left[H + \left(1 - \frac{A}{T}\right)h + \frac{2h}{\pi} \sin \frac{\pi A}{T} \sin \left(\frac{2\pi}{T} t + \varphi\right) \right] \sqrt{1 + \frac{m^2 d^2 \omega^2}{\mu^2}}, \quad (5)$$

where ξ is the zeta-potential;

μ is the dynamic viscosity coefficient of water;

m, d are mass and diameter of liquid molecules;

ω is the oscillation frequency of AC voltage component.

Effective mobility is:

$$\vartheta_e = \frac{\varepsilon \xi}{\mu} \left[H + \left(1 - \frac{A}{T}\right)h + \frac{\sqrt{2}h}{\pi} \sin \frac{\pi A}{T} \right] \sqrt{1 + \frac{m^2 d^2 \omega^2}{\mu^2}}. \quad (6)$$

The mobility of water molecules ϑ_{e-} at alternating voltage is determined by expression (6), and by ϑ_{e-} at a constant voltage. Their ratio is:

$$\frac{\vartheta_{e-}}{\vartheta_{e-}} = 1 + \frac{h}{H} \left(1 - \frac{A}{T}\right) + \frac{\sqrt{2} \left(\sin \frac{\pi A}{T}\right) h}{\pi H} \sqrt{1 + \frac{4m^2 d^2 \pi^2}{T^2 \mu^2}}. \quad (7)$$

where $\vartheta_{e-} = \frac{\varepsilon \xi H}{\mu}$.

Consider the relationship between mobility of water molecule and the reciprocal of the duty cycle $X = \frac{A}{T}$. Expression (7) taking into account X is:

$$F(X) = \frac{g_{e-}}{g_e}(X) = 1 + \frac{h}{H}(1-X) + \frac{\sqrt{2} h}{\pi H} \sin \pi X + \frac{\pi H}{\sqrt{1 + \frac{4m^2 d^2 \pi^2}{T^2 \mu^2}}} \sin \pi X. \quad (8)$$

To maximize expression (8), we find the first and second derivatives:

$$\frac{\delta F}{\delta X} = -\frac{h}{H} + \frac{h\sqrt{2}}{H \sqrt{1 + \frac{4m^2 d^2 \pi^2}{T^2 \mu^2}}} \cos \pi X, \quad (9)$$

$$\frac{\delta^2 F}{\delta X^2} = -\frac{h\pi\sqrt{2}}{H \sqrt{1 + \frac{4m^2 d^2 \pi^2}{T^2 \mu^2}}} \sin \pi X, \quad (10)$$

As $\frac{\delta^2 F}{\delta X^2} < 0$ for $0 < X < 1$, then any root of equation:

$$\frac{\delta F}{\delta X} = 0 \quad (11)$$

At the interval $]0;1[$ gives the function $F(X)$ the largest value in this interval. Combining (9), (11), we obtain:

$$\cos \pi X = \frac{\sqrt{1 + \frac{4m^2 d^2 \pi^2}{T^2 \mu^2}}}{\sqrt{2}}. \quad (12)$$

In the first approximation $\sqrt{1 + \frac{4m^2 d^2 \pi^2}{T^2 \mu^2}} \approx 1$, so $\cos \pi X = \frac{1}{\sqrt{2}}$. Hence $X=1/4$, and duty factor $T/A=4$.

The obtained pulse duty factor will ensure destruction of clusters, an increase in mobility of water molecules, and, consequently, will increase the efficiency of EOD process. The remaining set of pulse parameters was determined experimentally [7].

Figure 4 shows the curves of change in R of EM insulation groove during EOD by voltage of various shapes. Analyzing curves 1, 2, we see that EOD efficiency is several times higher for EOD device, at the output of which, in addition to the constant, a pulsed component is also generated. After 4 hours, the EM insulation R when using DEOD with a pulsed voltage component reached 400 kOhm. At the same time, the EM insulation R during EOD with only constant voltage was 130 kOhm.

4 Conclusions

1. Application of new method of cold drying of EM insulation eliminates thermal destruction, reduces energy consumption by 2-3 orders of magnitude and labour costs by 2-3 times.

2. Hydrated water molecules and ammonia ions become inactive, which reduces the EOD efficiency.

3. Imposition of additional pulsed electric field on EM insulation system during EOD increases the penetration ability, mobility of ions and water molecules and prevents their hydration.

4. A new EOD method was developed using a pulsed voltage component with a duty factor of 4. It increases the drying speed of EM insulation by three times.

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