Innovative technology for dismantling the windings of electric motors using ultrasonic radiation

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Abstract. The use of ultrasonic radiation showed an advantage over the existing methods of dismantling the windings of electric motors (EM). The method is based on the cavitation impact of ultrasonic vibrations and the capillary effect, which helps the caustic soda solution (NaOH) to quickly penetrate into the thickness of the lacquer impregnation and contribute to the destruction of the insulation from the inside. Analysis of dismantling of EM windings on the basis of ultrasound was carried out by the method of active experiment planning. As a result, a mathematical model of the process of removing the “burnt” EM winding was obtained, and the optimal parameters of power and duration of ultrasound, the temperature and the concentration of the NaOH solution were determined. Asynchronous electric motors (AEM) are the most widespread receivers of electrical energy. To ensure reliable and trouble-free operation of the AEM as a part of technological processes, it is necessary to implement completely new methods for their protection with the possibility of preventive action, carrying out continuous monitoring of motor parameters. In contrast to the systems of classical protection, which are triggered by faults, the system being developed makes it possible to avoid severe emergencies by predicting and detecting damages at an early stage.

1. Introduction

Currently, electric motors are the largest consumers of electrical energy [1-5]. According to many sources, they consume over 80% of all electricity produced in the country. In industry and agricultural production, EMs are operated under very harsh conditions. High humidity, dustiness, aggressive environment, low quality of the supply voltage annually lead to failure of up to 20% EM [6]. EM failure results in great damage to enterprises of the agro-industrial complex and other industries. The specifics of agricultural enterprises are associated with the process of life support of biological objects, smelting of metal in metallurgical plants [7-10]. Consequently, the failure of technological operations due to the failure of EM leads to a decrease in productivity. Failure of EM leads to process downtime and product damage. In addition to the main damage to the enterprise, there may be additional losses - reducing the levels of electrical and fire safety associated with possible short circuits in the windings of the stator or rotor of the damaged EM. In the technology of their repair, the dismantling of the burned-down stator
winding is important. Repaired EM must meet the requirements of reliability and efficiency in further work.

2. Methods
The existing methods of winding dismantling have a number of disadvantages: increased energy consumption, deterioration of steel electrical characteristics, mechanical damage to the EM stator package, negative impact on the environment, etc. [11]. The basis of the developed method is cavitation impact of ultrasound. The use of ultrasound increases the capillary effect, as a result of which the working solution of NaOH penetrates faster into the thickness of winding. As a result, the process of dissolving the impregnating composition and releasing the burnt winding is accelerated. In contrast to the known methods, the proposed one is the most efficient since it does not have a destructive effect on the useful elements of EM construction, is environmentally friendly and less energy consuming.

To find the optimal parameters of factors which act on the EM winding in order to dismantle it, a multifactorial active experiment was conducted. The temperature of NaOH alkaline solution, the solution concentration, the power of ultrasonic radiation and the duration of exposure were chosen as influencing factors. A number of exploratory experiments were conducted in advance to select the intervals of factors variation [12]. For this, it was necessary to develop the hardware complex and the design of the ultrasonic bath [11].

Figure 1 shows the block diagram of the hardware complex [13].

![Figure 1. Block diagram of the hardware complex.](image)

An alternating voltage of 220 V is supplied to the input of the hardware complex. The power converter PowC is designed to convert an alternating voltage of one frequency into an alternating voltage of another frequency. Rectifier V converts AC voltage to DC voltage. The master oscillator MO converts the DC voltage into a rectangular AC of a given frequency. The main function of the CU control unit is to turn on or turn off the generator through predetermined temporal characteristics using timer T. CU, using a thyristor voltage regulator, changes the voltage level applied to tubular heating element (THE), thereby maintaining the desired bath temperature. The THE heating temperature is adjusted through feedback (FS 2) using DT. The feedback signal (FS) is removed from DT and fed to CU. It is the signal level of FS which determines the THE temperature. The transformer T1 provides galvanic isolation of the power converter (PowC) from the ultrasonic transducer (UST). The inductance L is chosen in such a way that, coupled with MO and UST, it creates a voltage resonance and bring the UST to a working state. The current transformer T2 is necessary for galvanic isolation from the mains voltage and for setting a specific mode of the piezoelectric ultrasound transducer: manual, semi-automatic and automatic. Feedback FS 1 adjusts the frequency of MO with temperature changes in the characteristics of ultrasound. The controller module is included in CU and is designed to control the process: a change of THE temperature and UMO power.

The exploratory studies using the hardware complex and the ultrasonic bath were carried out using the specially made EM winding layouts, known as statorets (Figure 2). The statorets were made according to GOST-IEK 60851-3–2011 and were models of EM slot and interphase insulation.
Figure 2. The stator model.

The model is a section of a square shaped section pipe, inside of which there is a single-layer winding made of PETV-2 copper wire with of 1 mm diameter with a number of turns equal to 120. The slot insulation is made of a synthetic cardboard. To give strength to the frontal parts of the winding, a band of cotton electrical tape was applied. The stator model was impregnated with varnish ML-92.

3. Results

The results of exploratory research are shown in Figure 3. As it can be seen, for 2% concentration of NaOH and ultrasound exposure (curve 3“), we get almost the same result as for 10% concentration of the solution without ultrasound (curve 1). So, ultrasound enhances the effect of lacquer impregnation destruction for about 5 times, which is quite significant.

Figure 3. Relationship between the bending of EM winding frontal parts and the force of exposure and NaOH concentration:
1 - for k=10%;
2 - for k=5%;
3 - for k=2%;
4 - or k=0%;
1"- for k=10% and ultrasound treatment;
2"- for k=5% and ultrasound treatment;
3"- for k=2% and ultrasound treatment.

These experiments allowed us to determine the factor variation levels (Table 1).

| Independent parameters | Designation | Variation levels | Variation level |
|------------------------|-------------|------------------|----------------|
| Treatment duration, min| X1          | -1 30 100 170    | 70             |
| Temperature, °C        | X2          | 0 20 35 50       | 15             |
| Ultrasonic radiation power, W| X3        | 0 40 90 140     | 50             |
| Solution concentration, %| X4        | 0 2 4.5 7       | 2.5            |

For the correct formulation of the experiment and for obtaining reliable results, we used a second-order rotatable plan with star points. The advantage of such plans is a small number of experiments. So, with k = 4, the total number of experiments is 25. When using the rotatable plan, it is necessary to add the matrix of the plan to the matrix of the second order plan. 16 points are used as the “core” of the matrix, then 8 “star” points and one zero point are added. The value of the star shoulder was 1.414.

The mechanical characteristics were chosen as the response function: residual strength of the winding and adhesion of the windings between each other [13]. To remove the mechanical characteristics we developed a stand (Figure 6) [14]. It allows one to explore the impact of destructive factors on the impregnation of the EM winding with different levels of exposure, presented in table 1. The levels of
influence of factors vary in each experiment and in different ways destroy the solidity of the lacquer impregnation of the EM winding.

The stand (Figure 4) consists of a bed 1, on which fork 2 of arm mounting 5 is mounted, a platform for interchangeable nozzles 16, and supporting table 4 for a strain gauge 9 of an electronic dynamometer. Supporting table 4 has a height adjustment and is fixed with a bolt. The platform for replaceable nozzles consists of welded corners on the sides of the profile of the frame and the stop. To install the nozzle, simply insert it into the grooves and push it in until it stops. The arm 5 is attached to the fork 2. The shoulders of arm 5 are perpendicular to the axis of its rotation.

Figure 4. The stand construction: 1 - bed; 2 - fork; 3 - replaceable nozzle; 4 - table for strain gauge; 5 - arm; 6 - stator model; 7 - indenter; 8 - tightening device; 9 - strain gauge; 10 - dial indicator; 11 - ligging loop; 12 - wire rope; 13 - supporting arm; 14 - fixing clamp; 15 - dial indicator stock; 16 - area for replaceable nozzles.

The stator models are fixed on interchangeable nozzles (Figure 5) with the help of metal plates tightened with a wing nut. The arrows indicate the forces applied to the stator model when determining the response functions.

Figure 5. Replaceable nozzle of the stand:
1 - to determine the residual strength of the frontal part;
2 - to determine the residual adhesion of the windings between each other;
3 - to determine the effort of pulling out the winding.

Figure 6. Indenters:
1 - to determine the residual strength of the frontal part;
2 - to determine the residual adherence of the windings between each other;
3 - to determine the effort of pulling out the winding.

For each nozzle, an indenter is provided, without which it is impossible to test the mechanical characteristics of the EM winding (Figure 6).

The stand (see Figure 4) makes it possible to test all the response functions for constructing mathematical models of the process of dismantling the “burnt” EM windings.

As a result of the experiment, mathematical models (1) and (2) of destruction of a burnt EM winding were obtained with the aim of its further “easy” dismantling. The significance of the regression
coefficients was tested according to the Student's criterion, the adequacy of the model was determined by the Fisher criterion, the reproducibility of the experiments was measured by the Cochren criterion.

Regression equation for the function of residual strength:
\[
Y(X_1, X_2, X_3, X_4) = 0.381 - 0.097X_1 - 0.073X_2 - 0.051X_3 - 0.018X_4 -
0.013X_1X_2 + 0.037X_2X_3 - 0.046X_2X_4 - 0.03X_2X_4 -
-0.049X_1X_2X_4 + 0.023X_3X_4 - 0.116X_2X_4 +
+0.134X_1X_2X_3X_4 + 0.04X_1^2 - 0.023X_2^2 + 0.065X_4^2. \tag{1}
\]

Regression equation for the function of residual adherence:
\[
Y(X_1, X_2, X_3, X_4) = 0.529 - 0.077X_1 - 0.057X_2 - 0.059X_3 - 0.03X_4 -
-0.029X_1X_2 + 0.035X_2X_3 - 0.018X_1X_3 - 0.04X_2X_4 - 0.023X_3X_4 -
-0.028X_1X_2X_4 - 0.097X_2X_3X_4 + 0.112X_1X_2X_3X_4 +
+0.055X_1^2 - 0.015X_2^2 - 0.026X_3^2 + 0.083X_4^2. \tag{2}
\]

From equations (1) and (2) it can be seen that duration of factors \( X_2, X_3, X_4 \) exposure has the greatest contribution to the destruction of the monolithic varnish impregnation of the EM winding. The value of the factor \( X_1 \) can be reduced several times compared with the value of this factor in the existing methods of dismantling and thereby reduce the time for dismantling the EM winding. The factors of NaOH solution temperature \( X_2 \) and ultrasound power \( X_3 \) are also very significant and make almost the same contribution to softening of EM winding. The NaOH concentration \( X_4 \), i.e. concentration of the chemically active environment, has the least impact on the process of dismantling the EM winding, which is very important because it provides an opportunity to significantly reduce environmental damage and preserve the health of staff. In our case, it was possible to reduce the concentration of NaOH by almost 2 times.

To obtain the optimal parameters of the influencing factors on the process of destruction of the winding of a burnt EM, we find the partial derivatives of each factor and solve the resulting system of equations for each response function:
\[
\frac{\partial Y(X_1, X_2, X_3, X_4)}{\partial X_1} = 0; \quad \frac{\partial Y(X_1, X_2, X_3, X_4)}{\partial X_2} = 0; \quad \frac{\partial Y(X_1, X_2, X_3, X_4)}{\partial X_3} = 0; \quad \frac{\partial Y(X_1, X_2, X_3, X_4)}{\partial X_4} = 0. \tag{3}
\]

Having solved the system of equations (3), we obtain in relative units: for residual strength: \( X_1 = 1.024; \ X_2 = 1.03; \ X_3 = 0.525; \ X_4 = 0.738 \), for adhesion of the windings: \( X_1 = 0.83; \ X_2 = 1; \ X_3 = 0.596; \ X_4 = 0.659 \).

In actual values:
\[
X_1 = X_{1a}^0 - \frac{X_{1a}^0 - X_{1a}^0}{\Delta X_1}; \quad X_2 = X_{2a}^0 - \frac{X_{2a}^0 - X_{2a}^0}{\Delta X_2}; \quad X_3 = X_{3a}^0 - \frac{X_{3a}^0 - X_{3a}^0}{\Delta X_3}; \quad X_4 = X_{4a}^0 - \frac{X_{4a}^0 - X_{4a}^0}{\Delta X_4}; \tag{4-7}
\]

Where \( X_{1a}^0, X_{2a}^0, X_{3a}^0, X_{4a}^0 \) are actual values of the factors; \( X_{1a}^0, X_{2a}^0, X_{3a}^0, X_{4a}^0 \) are the zero-level variation of factors; \( \Delta X_1, \Delta X_2, \Delta X_3, \Delta X_4 \) are the intervals of factors variation.

Taking into account equations (4) - (7), the optimal values \( X_1, X_2, X_3, X_4 \) are obtained in actual units for the process of the most efficient dismantling of EM windings using ultrasonic treatment. Table 2 shows the optimal values of factors for which the residual strength and adhesion of the EM winding are minimal. At the same time, the optimal solution temperature for NaOH is 30% lower than the temperature which is characteristic for the leaching method [6]. This makes it possible not only to reduce energy consumption with the developed method of disassembling the EM windings, but also to maintain the insulation between the plates, as well as electrophysical characteristics of the stator steel by reducing the penetration of NaOH molecules into the space between the magnetic core plates.

**Table 2.** The values of optimal parameters.

| Factors          | Minimal values of residual strength | Minimal values of residual adhesion |
|------------------|------------------------------------|------------------------------------|
| \( X_{1a}^0 \), min | 171                                 | 159                                |
From equations (1) and (2), partial regression equations were obtained, which were used to construct the surfaces of response functions for residual strength and residual adhesion of the EM windings using the Mathcad mathematical package, shown in Figure 7. At $X_1 = 171$ min. residual strength $X_4 = 6.3\%$, other parameters: $X_2 = 51\, ^\circ \text{C}$ and $X_3 = 116\, \text{W}$. At $X_1 = 159$ min. Adhesion $X_4 = 6.1\%$, other parameters: $X_2 = 50\, ^\circ \text{C}$ and $X_3 = 120\, \text{W}$.

\begin{align*}
X_2^3 & \, ^\circ \text{C} \\
X_3^3 & \, \text{W} \\
X_4^3 & \, \% \\
50.45 & \\
116.25 & \\
6.3 & \\
50 & \\
120 & \\
6.1 &
\end{align*}

\begin{align*}
y &= 0.5535 - 7.7 \times 10^{-3} \cdot X_2 - 3.9 \times 10^{-3} \cdot X_3 + \\
&\quad + 6.3 \times 10^{-5} \cdot X_2 \cdot X_3 - 8.3 \times 10^{-5} \cdot X_2^2 \\
\text{a)} \\

y &= 0.935 - 6.7 \times 10^{-3} \cdot X_2 - 1.5 \times 10^{-3} \cdot X_3 + \\
&\quad + 3.8 \times 10^{-5} \cdot X_2 \cdot X_3 - 5.4 \times 10^{-5} \cdot X_2^2 - 10^{-5} \cdot X_3^2 \\
\text{b)}
\end{align*}

\textbf{Figure 7.} Surfaces of response functions:
\begin{itemize}
  \item a) Residual strength at $X_1 = 171$ minutes; $X_4 = 6.3\%$;
  \item b) Residual adhesion at $X_1 = 159$ minutes; $X_4 = 6.1\%$.
\end{itemize}

\section*{4. Conclusion}
Thus, the optimal parameters of the process of dismantling the EM windings using ultrasound are obtained. These parameters should be incorporated into the structural and electrical parts of the hardware complex for dismantling EM serial windings for the purpose of production tests of the developed method of their repair in electrical repair shops.

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