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DETECTING DEVELOPING DEFECTS IN ELECTRIC DRIVE MOTOR WINDINGS THROUGH MULTI-PARAMETER MONITORING OF INSULATION CONDITION

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Abstract— The process of detecting insulation faults in motor windings is one of the key tasks of technical diagnostics aimed at ensuring the reliability and safety of electric machines. Along with technical monitoring tools, the human factor also plays an important role in this process, influencing the quality of diagnostic procedures and the decision-making based on measurement results.The service life of electric motors used in various production processes depends largely on the condition of the winding insulation. Damage to the insulation can lead to emergency situations. This article discusses how to assess the condition of winding insulation and identify defects in the early stages of operation. We present a multiparameter control method for detecting developing defects in the stator windings of electric drive motors. This method is based on assessing insulation resistance, capacitance, dielectric loss tangent, voltage recovery time, and dielectric absorption coefficient. To determine the criteria that characterize the winding condition, an equivalent circuit of the insulation system was proposed, and experimental studies were conducted. The characteristic parameters of the insulation of the phase windings of one of the motors were examined at temperatures of 100°, 120°, 130° and 140°C. Analysis of the results shows that a comprehensive approach to assessing the insulation state of electric drive motors that takes climatic factors into account increases the reliability of the equipment and improves operation and maintenance processes. These results can be used to develop intelligent systems for monitoring and diagnosing electric drive motors.
Keywords— multiparameter monitoring, isolation, phase winding, electric drive motor.

I. INTRODUCTION

The perception of the facility's condition, formed through organized and systematic monitoring, contributes to the production of competitive products. This is because periodic damage or equipment failure requires additional financial resources and, in some cases, an unplanned shutdown of the technological process. This may result in the production of low-quality, low-productivity products. The normal operation of various industrial sectors cannot be imagined without synchronous and asynchronous motors of different power levels [1-3]. However, analysis has shown that these electric motors have a high failure rate [4,5]. According to existing analyses, 20 to 25% of operating electric motors fail each year [6]. In addition to the direct losses caused by motor failure, electrical and fire safety are reduced due to short circuits in the electric motor circuit [7-11]. Therefore, tasks that aim to detect and prevent malfunctions in electric drive motors in a timely manner and improve the quality of their monitoring are relevant to any industry. The service life of an electric motor depends largely on the state of the winding insulation, transient phenomena, and load asymmetry of the motor phases. When an electric motor is started, the stator current can increase up to six times the rated current. This can cause the electrical insulation of the motor circuit to deteriorate over time. Due to low supply voltage quality, overloads, and frequent stator winding shutdowns and stops, microdefects develop over time, leading to emergency situations. Considering the above, this paper examines the insulation condition of the stator winding, which is the most vulnerable element of an electric motor, by monitoring it. Many researchers have focused on evaluating the insulation condition of electric motor windings and identifying potential damage [12-17].

The authors of paper [12] considered issues related to the universal and rapid monitoring of electric motor performance. For electronically controlled motors, they proposed registering a large number of parameters in real time. By analyzing these parameters in real time, anomalies can be identified and failures can be prevented in a timely manner. This paper describes the main components of the proposed monitoring system and the process of analyzing the collected data. [13] considers the detection of inter-turn short circuits using a Kalman filter. This method enables the output of motor current and voltage signals through a Kalman filter and the evaluation of windings' condition using a statistical index of inter-turn short circuits. This method effectively works with large load changes and in the presence of signal noise.

In [14], the detection of inter-turn short circuits was implemented using an algorithm that analyzes magnetic field leakage signals during generator operation.

A model that allows for the rapid and accurate detection of asymmetrical short circuits in the stator windings of a synchronous machine is of interest. This model was developed on the basis of an artificial neural network [15]. In accordance with IEEE standards, it enables accurate decision-making regarding the need to limit the operating time of a damaged generator.

There is a known method proposed for remote assessment of the winding condition [16]. In this approach, an HSCT current transformer was used to measure the differential current, this was replaced by a conventional current transformer. This method enables the assessment of the winding's state at any given time.

The partial discharge control method [17] is also used to monitor the state of the stator trajectory. This method provides the most complete information about various defects in the motor insulation at an early stage of their development. This method is recommended for high-voltage motors.

Despite the numerous studies conducted to assess the condition of the winding, the dynamics of changes in the technical condition of the winding insulation and the early detection of damage remain of scientific and technical interest. This article addresses these topics. The purpose of this work is to propose a methodology that can assess changes in the insulation state of operated electric drive motor windings using integrated monitoring, ensuring early defect detection.

II. MATERIALS AND METHODS

A. Basic criteria for monitoring the insulation condition of the windings of an electric drive motor

Short circuits may occur between the phase windings of electric motors during operation. The main reasons for their occurrence are:

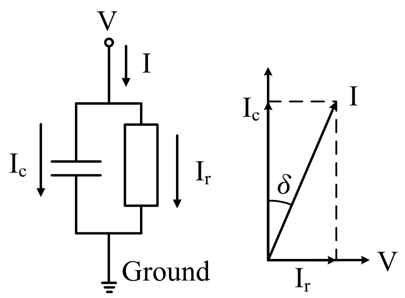
- Current overload. When the motor load exceeds the rated value, the stator winding heats up and the insulation breaks down in some places, causing a short circuit between adjacent windings.
- Damage caused by mechanical phenomena. Vibrations in the motor and improper fastening can damage the windings' insulation.
- Contamination of the windings. Dust, moisture, and oil can reduce the dielectric strength of the insulation.
- Overvoltage: Impulse overvoltage can break through the insulation.

Regardless of the cause of the short circuit, it is clear that it resulted from damage to the winding insulation. This circumstance formed the basis for monitoring the insulation's condition. This paper proposes a methodology for monitoring the insulation condition of electric drive motor windings using multiple parameters. This is accomplished by evaluating the insulation resistance, dielectric loss tangent, voltage recovery time τ , and dielectric absorption coefficient K . Comments on these criteria are provided.

Determining the insulation resistance of the motor winding provides a general assessment of its contamination and humidity levels.

The electrical equivalent circuit of an insulating material consists of a parallel-connected capacitor and resistor (Fig. 1). The current (I) flowing through the insulation consists of capacitive and resistive components. The dielectric loss tangent shows how much energy the material "loses" during polarization. It is the tangent of the angle formed by the capacitive and resistive currents.

$tg\delta = I_a / I_r$



(a) (b)

Fig. 1. (a) Equivalent circuit of the electrical insulation system and (b) vector diagram depicting capacitive and active currents

Due to the excellent insulation of the stator winding, the current I has a predominantly capacitive nature since the capacitive resistance is significantly lower than the active resistance (δ is close to 0). The active component of the current increases with increasing dielectric losses of the insulation, indicating its aging.
Another important parameter characterizing the quality of winding insulation is the voltage recovery time τ. This time is equal to the product of the winding insulation resistance R and the capacitance.
The dielectric absorption coefficient K is determined by the ratio of the recovery and charging voltages.

B. Monitoring implementation algorithm.

To monitor the criteria that characterize the condition of the windings, an equivalent circuit diagram of the insulation system of a three-phase electric motor's windings was used (Fig. 2). The capacitances between the windings of phases ab, bc and ac are designated as C_{ab}, C_{bc}, C_{ac} respectively, and the insulation resistances are designated as R_{ab}, R_{bc}, R_{ac}. The capacitances between the windings of phases a, b, and c and the housing are designated as $C_{a1g}, C_{b1g}, C_{c1g}$ respectively, and the insulation resistances are designated as $R_{a1g}, R_{b1g}, R_{c1g}$, respectively.

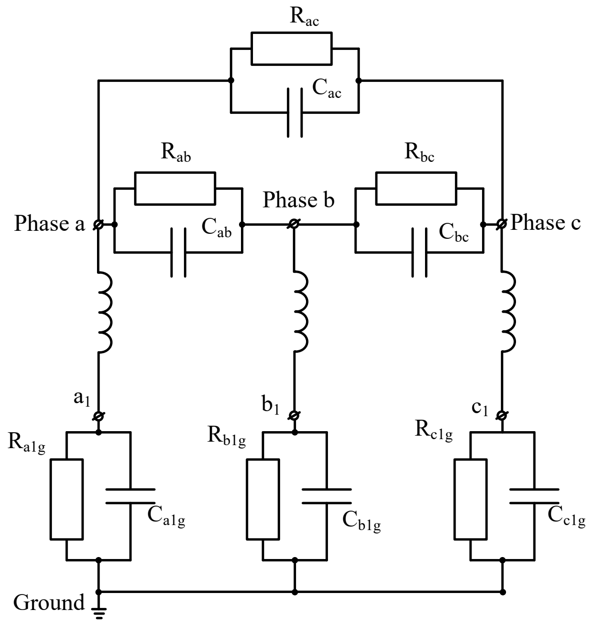


Fig. 2. Equivalent circuit scheme of the insulation system of the windings of a three-phase electric motor

Figure 3 shows a diagram of how to measure the capacitance of each phase relative to the housing.

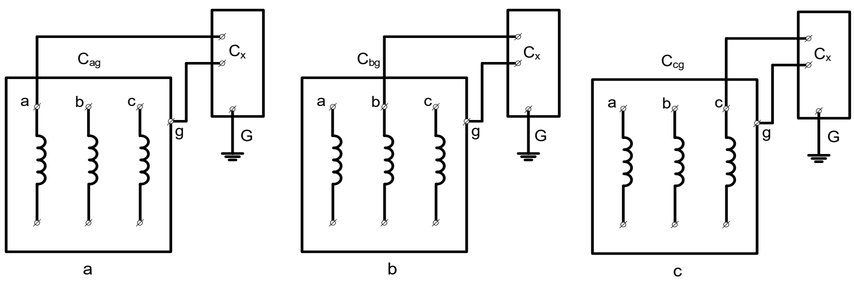


Fig. 3. Capacity measurement diagram: a: phase **a** relative to the housing; b: phase **b** relative to the housing; c: phase **c** relative to the housing

The test procedure is presented below. First, a voltage of 500 V DC is applied successively between phases A, B and C of the winding and the motor housing (Fig. 4). Fifteen minutes after applying the voltage, the charged end of the winding and the housing are short-circuited. After disconnecting them, the recovery voltage is measured with an electrostatic voltmeter. Using a stopwatch, the rate of voltage recovery is recorded until the voltage stabilizes. Once the voltage has stabilized, a repeated discharge is performed to record the value of the second recovery voltage. After the motor winding insulation self-discharges, the self-discharge time is recorded.

Fig. 4. Test scheme

Capacitance (C) and tangent delta (tgδ) are measured using a P5079 type automatic digital AC bridge. The bridge operates using sensors. The insulation capacitances (C_{ag}, C_{bg} and C_{cg}) of the motor windings relative to the housing and the tangent of the dielectric loss angle of the insulation measured. First, the tests were carried out at room temperature (25°C). Then, the tests continued in a heat chamber at temperatures of 100°C, 120°C, 130°C and 140°C.

III.RESULTS

Experimental studies were conducted at a temperature of 25°C for 4 motors with a capacity of 180 kV, which are:
1. 4AA56.B4Y3 type motor, service life 1 year;
2. АИР56.B4Y3 type motor, service life 1 year;
3. 4AA56.A2Y3 type motor, service life 1 year;
4. 4AA56.B4Y3 type motor, service life 3 years.

Table 1 presents the characteristic parameters of the insulation of phase windings of various asynchronous motors.

TABLE 1 EXPERIMENTAL DATA ON THE INSULATION CHARACTERISTICS OF PHASE WINDINGS OF VARIOUS ASYNCHRONOUS MOTORS

Motor number	**Phase**	**C, pcf**	**tgδ**	**R*10[10], Ohm**	**τ, sec**
1	Motor type 4AA56.B4Y3, U=220/380V, I=1.16/0.67A, cos φ=0.64, n=1370 RPM				
	ag	364.6	2.0	226	824
	bg	359.3	2.7	208	747
	cg	349.3	1.9	250	873
2	Motor type АИР56.B4Y3, U=220/380V, I=1.09/0.63A, cosφ=0.68, n=1350 RPM				
	ag	368	4.5	230	846
	bg	365	3.95	179	654
	cg	371.4	3.2	220	817
3	Motor type 4AA56.A2Y3, U=220/380V, I=0.95/0.55A, cos φ=0.76, n=2760 RPM				
	ag	287.7	3.4	233	670
	bg	279.5	3.3	224	626
	cg	287.3	3.3	236	678
4	Motor type 4AA56.B4Y3, U=220/380V, I=1.16/0.67A, cos φ=0.64, n=1370 RPM				
	ag	108.1	3.8	160	653
	bg	387.8	0.39	211	839
	cg	396.7	0.69	157	623

Analysis of the results shows that the differences in values for parameters characterizing the insulation conditions of all windings in phases A, B, and C of Motor 3 are insignificant. The insulation of phase C windings of motors 1, 2, and 3 is in good condition. Despite having identical technical data, motors 1 and 4 have significantly different values for the parameters that characterize the insulation condition of their windings. This difference is explained by the operating conditions. In partular, motor 4AA56.B4Y3, number 4, was operated under normal and wet conditions for five years.

For the AIR56.B4У3 motor, numbered 1, tests were conducted at temperatures of 100°C, 120°C, 130°C and 140 °C. The maximum winding test temperature was selected taking into account the maximum winding heating value established for these motors by the standard. The motor test results are presented in Table 2.

TABLE 2 RESULTS OF TESTING THE INSULATION CONDITION OF PHASE WINDINGS OF THE AIR56.B4У3 MOTOR UNDER VARIOUS TEMPERATURE CONDITIONS

Test temperature	C, pcf	tgδ	R*10-12, ohm	t, sec	K
for ag, U= 500V					
25 ºC	368	0.0445	2.3	845	0.72
100 ºC	391	0.0539	1.34	524	0.77
120 ºC	400.6	0.0729	0.5	202	0.83
130 ºC	404.6	0.0789	0.37	148	1.06
140 ºC	419.7	0.1118	0.29	122	0.72
for bg, U= 500V					
25 ºC	365.5	0.0395	1.79	654	0.8
100 ºC	396.2	0.0529	1.11	440	0.81
120 ºC	410	0.0809	0.47	156	0.83
130 ºC	322.8	0.0859	0.38	152	0.8
140 ºC	436.3	0.1108	0.22	96	0.68
for cg, U= 500V					
25 ºC	371.4	0.0328	2.2	817	0.88
100 ºC	390.7	0.0539	1.28	501	0.36
120 ºC	399	0.0915	0.55	219	0.8
130 ºC	417.7	0.0998	0.37	154	0.75
140 ºC	430.5	0.1118	0.21	90	0.66

Changes in insulation resistance, voltage recovery time, and tan δ between the phase windings and the housing were observed under different temperature conditions.

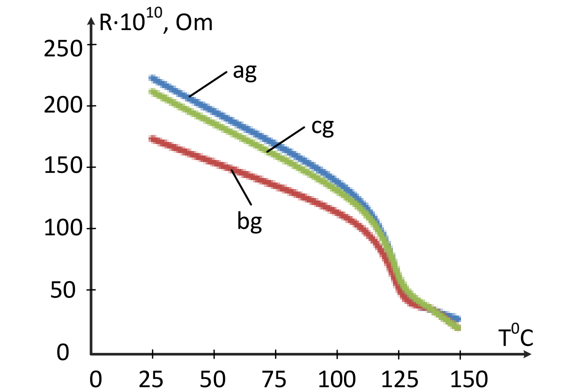


Fig. 5. Change in insulation resistance between phases a, b, c and the housing at temperatures of 25-140°C

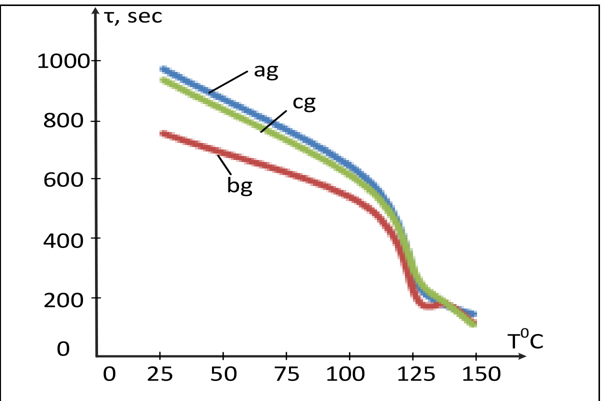


Fig. 6. Change in voltage recovery time τ between phases a, b, c and the housing at temperatures of 25-140°C

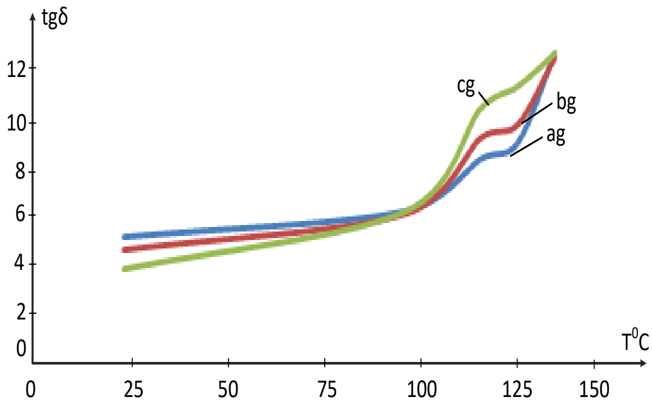


Fig. 7. Changes in tgδ between phases a, b, c and the housing at temperatures of 25-140°C

Tests conducted at different temperatures show that the values of insulation resistance, dielectric loss tangent, and voltage recovery time change significantly, while the change in the dielectric absorption coefficient is negligible.

The results obtained indicate that the performance of all observed characteristic parameters deteriorates with increasing temperature. The dependencies presented in Figures 5–7 confirm the importance of insulation resistance, discharge time, and tgδ for ensuring the motor's reliable operation under various conditions.

IV. CONCLUSIONS

The detection of insulation faults in motor windings is not only a technical task but also has a psychological dimension. The human factor plays a significant role in diagnostics, influencing the reliability of control and the efficiency of preventive maintenance. Applying methods of applied psychology in technical diagnostics helps reduce human error and creates safer, more productive working conditions for specialists.
At the same time, the authors propose a multi-criteria method for detecting developing insulation defects in electric motor windings. By assessing multiple parameters—such as insulation resistance, capacitance, dielectric loss tangent, voltage recovery time, and dielectric absorption coefficient—simultaneously, the accuracy of defect detection is increased. The results can be used to develop intelligent monitoring systems and guide further research on the effects of environmental factors like atmospheric pressure and air pollution, as well as on real-time monitoring using machine learning.

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