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Inhalt / Content

CHAPTER 1
DEVELOPMENT OF TECHNOLOGY OF COOKIE COOKIES ACCORDING TO THE TREND "CLEAN LABEL"

Introduction 7
1.1. Current trends in biscuit production 8
1.1.1. Characteristics of the current state of biscuit production 8
1.1.2. Analysis of the recipe composition and technology of biscuit biscuits 10
1.1.3. Prospects for the production of products according to the "CLEAN LABEL" trend 12
1.2. Development of biscuit technology based on high-oleic sunflower kernel meal under the "CLEAN LABEL" trend 16
1.2.1. Justification of the use of high-oleic sunflower seed kernel meal in the production of biscuit biscuits 16
1.2.2. Scientific justification and development of the recipe composition and technology of biscuit biscuits based on high-oleic sunflower seed kernel meal high oleic sunflower seed kernel meal 22
1.2.3. Standardization of quality and safety indicators of biscuits based on high-oleic sunflower seed kernel meal 34
Conclusions 37

CHAPTER 2
SYNERGY OF SYSTEMS - SOCIO-CYBER-PHYSICAL SYSTEMS (SCPS)

Introduction. Historical aspects of the computer systems evolution. Shifting paradigms of computerisation 38
2.1. Definitions of cyber-physical systems and it composition 40
2.2. General specification of industrial SCPS. A railway marshalling yard as an example of a facility for the implementation of the SCPIS 42
2.3. Extended concept of architecture of socio-cyber-physical systems 48
2.4. Changes in approaches to design. SCPS as a system of systems 51
Conclusions 56

CHAPTER 3
RESEARCH OF THE DIAGNOSTIC FEATURES INFLUENCE ON THE TECHNICAL CONDITION OF THE INTERPHASE AND WINDING INSULATION OF ELECTRIC MOTORS

Introduction 57
3.1. Method for determining the influence of diagnostic features on the state of insulation of electromechanical equipment 58
3.2. Simulation of the diagnostic signs influence on the technical condition of the interfacial insulation of electric motors 61

KAPITEL 3 / *CHAPTER 3* [3]
RESEARCH OF THE DIAGNOSTIC FEATURES INFLUENCE ON THE TECHNICAL CONDITION OF THE INTERPHASE AND WINDING INSULATION OF ELECTRIC MOTORS

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Introduction

Today's development of industrial enterprises involves the use of more modern electromechanical equipment (EME), but most of them, especially electric motors, have been in operation for more than 15 years and the service life according to the technical passport has almost or completely expired, and, as a rule, its technical condition is unsatisfactory. However, in accordance with the Technical Operation Rules [1], such equipment must meet all the requirements, which primarily include its reliability and efficiency during operation, which are negatively affected by both natural and operational factors. And in view of this, there is a need to conduct research in the technical diagnostics of the state of electrical equipment with the identification of possible damage and defects in it, taking into account at an early stage of their development and determining the residual life of the EME [2].

An effective way to identify possible damages and defects in the EME is to identify all possible signs and factors that negatively affect the technical condition and analyse the existing means of protection against the likely consequences of their occurrence [3].

At present, there are three areas of current monitoring of the technical condition and diagnostics of electrical equipment, which include parametric, preventive and damage diagnostics, aimed mainly at identifying the existing causes and consequences of negative anomalies and providing appropriate measures to prevent equipment failure, taking into account the collected information on the past and current state of electrical equipment [4]. All three areas involve several stages [5-7]: determination of probable signs of impact on the technical condition of the EMI; diagnostics of electrical equipment to identify damage and defects; forecasting the current technical condition

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of the EME with obtaining its residual service life. Currently, there are quite a few methods and tools for detecting damage, for example, diagnosing damage to bearings of rotating machines based on vibration studies using artificial neural networks [8] and wavelet transforms [9]; determining the stator fault of a three-phase synchronous motor using spectral analysis and neuro-fuzzy logic [10]; diagnosing damage to induction motors with the energy assessment of their parts in the event of a short circuit based on wavelet transforms [11]; diagnostics of electric motors for the presence of damage to switches when the rotor current and the corresponding voltage change [12]; determination of rotor damage using vibration signals [13,14]; diagnostics of insulation of synchronous motors and generator-motors provided that the parameters of the distributed current are directly monitored [15], the difference in measured stator currents [16] and partial discharges [17]. These methods do not consider the issue of diagnostic signs for the appearance of damage in the interphase and winding insulation, which is a rather urgent issue.

3.1. Method for determining the influence of diagnostic features on the state of insulation of electromechanical equipment

Modern well-known monitoring and diagnostic tools are based on the perception of the functional relationship between damages and defects and their causes under conditions of changes in the measured parameters. An example of such means is the maximum relay, which controls the change in current in electromechanical equipment, taking into account a given range of its values.

In the event of damage to electric motors, the value of the measured parameters usually changes within the appropriate limits in accordance with the statistical law that characterises the relationship between them. A special case of this relationship is the functional relationship, which characterises the correspondence between the values of one parameter and the values of another. An example is the correspondence of the insulation resistance to the average current supplied from the power supply, however,

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as a special case, the indicators of the features can take many values with different probabilities of their occurrence [18].

One of the methods is to determine the pairwise correlation between two indicators, taking into account only one factor influencing the variation of the resultant feature. In our case, the study is based on determining the correlation between the current and voltage of the electric motor stator phases and the interphase insulation resistances.

In view of this, the null hypothesis H_0 is put forward regarding the absence of the influence of a certain factor given the set of observations $y_i, i = 1,2,\dots,m$ on the obtained sample set of values $x_i, i = 1,2,\dots,m$ of the diagnostic indicator, but the alternative is the hypothesis H_1, which allows us to assert that the influence of a certain factor on this indicator is quite significant, taking into account the significance level $\alpha = 0{,}01$ [19]:

$$H_0: r_{xy} = 0\ , \tag{1}$$

$$H_1: r_{xy} \neq 0\ , \tag{2}$$

r_{xy} – correlation coefficient between the values of the diagnostic indicator and the influence factor [19]:

$$r_{xy} = \frac{K_{xy}}{\sigma_x \sigma_y}, \tag{3}$$

x i y – values of the indicators between which the correlation is searched;

K_{xy} – correlation moment,

σ_x i σ_y – correspond to the values of the standard deviations of the indicator and the influence factor.

The correlation coefficient should take a value between -1 and +1. The closer the result is to 1 in absolute value, the better the relationship, and the positive or negative sign of the coefficient indicates the direction of this relationship, i.e. '+' shows a direct relationship, and '-' shows an inverse relationship. If the correlation coefficient is zero, then there is no linear relationship between the attributes; and if the absolute value is one, then there is a functional relationship between these attributes.

The hypothesis is tested by checking its significance using the Student's t-test due to the significance of the correlation coefficient and its confirmation or refutation is determined in accordance with the following requirements [19]:

$$|z^*| < t_{1-\frac{\alpha}{2}}(n), \tag{4}$$

n – corresponds to the number of degrees of freedom, $n = m - 2$,

m – the total volume of the defined sample population,

$t_{1-\frac{\alpha}{2}}$ – quantile of the Student's distribution at the significance level α,

z^* – sample statistics of the criterion on relevant empirical data [18]:

$$z^* = \frac{r \cdot \sqrt{n}}{\sqrt{1-r^2}} \tag{5}$$

The determination of the probable dependencies between the current and voltage of the ED stator phases and the interphase insulation resistances was carried out on the basis of a computational experiment using the following technology:

1) the electric motor operation scheme was constructed using the generalised mathematical model (6) according to [20]:

$$\begin{cases} \overrightarrow{u_s} = r_s \cdot \overrightarrow{\imath_s} + \frac{d\overrightarrow{\psi_s}}{dt} + j \cdot \alpha_k \cdot \overrightarrow{\psi_s} \\ \overrightarrow{u_R} = r_R \cdot \overrightarrow{\imath_R} + \frac{d\overrightarrow{\psi_R}}{dt} + j \cdot (\alpha_k - p \cdot v) \cdot \overrightarrow{\psi_R} \\ \overrightarrow{\psi_s} = x_s \cdot \overrightarrow{\imath_s} + x_m \cdot \overrightarrow{\imath_R} \\ \overrightarrow{\psi_R} = x_m \cdot \overrightarrow{\imath_s} + x_R \cdot \overrightarrow{\imath_R} \\ m = k \cdot Mod(\overrightarrow{\psi_\imath} \times \overrightarrow{\imath_k}) \\ \overrightarrow{T_m} \frac{dv}{dt} = m - m_H \end{cases}, \tag{6}$$

де $\vec{u}, \vec{\imath}, \vec{\psi}$ – relative electromagnetic state changes;

α_k, v – relative parameters of stator frequency and rotor speed, respectively;

m – relative torque on the motor shaft;

$r_s, r_R, x_s, x_m, x_R, \overrightarrow{T_m}$ – relative model parameters [20].

However, in our case, a virtual model of the electric motor is used, which is based on the mathematical model (6) and represented by the corresponding block in the Matlab - Simulink program.

2) control devices are used;

3) measurements of phase currents and leakage currents at different loads and

different insulation resistances are performed;

4) the measurement results were processed accordingly to determine statistical relationships.

3.2. Simulation of the diagnostic signs influence on the technical condition of the interfacial insulation of electric motors

The influence on the technical condition of the interphase insulation of electric motors was determined using a computer model (Figure 1) consisting of a three-phase voltage source, an electric motor, resistors that are analogous to the insulation between the phases of the electric motor stator, and ammeters and an oscilloscope connected to the circuit to obtain measurements and observe mechanical parameters such as speed and torque. During the simulation, the resistors' resistance was changed and the values of the currents of the phases and the leakage current were recorded.

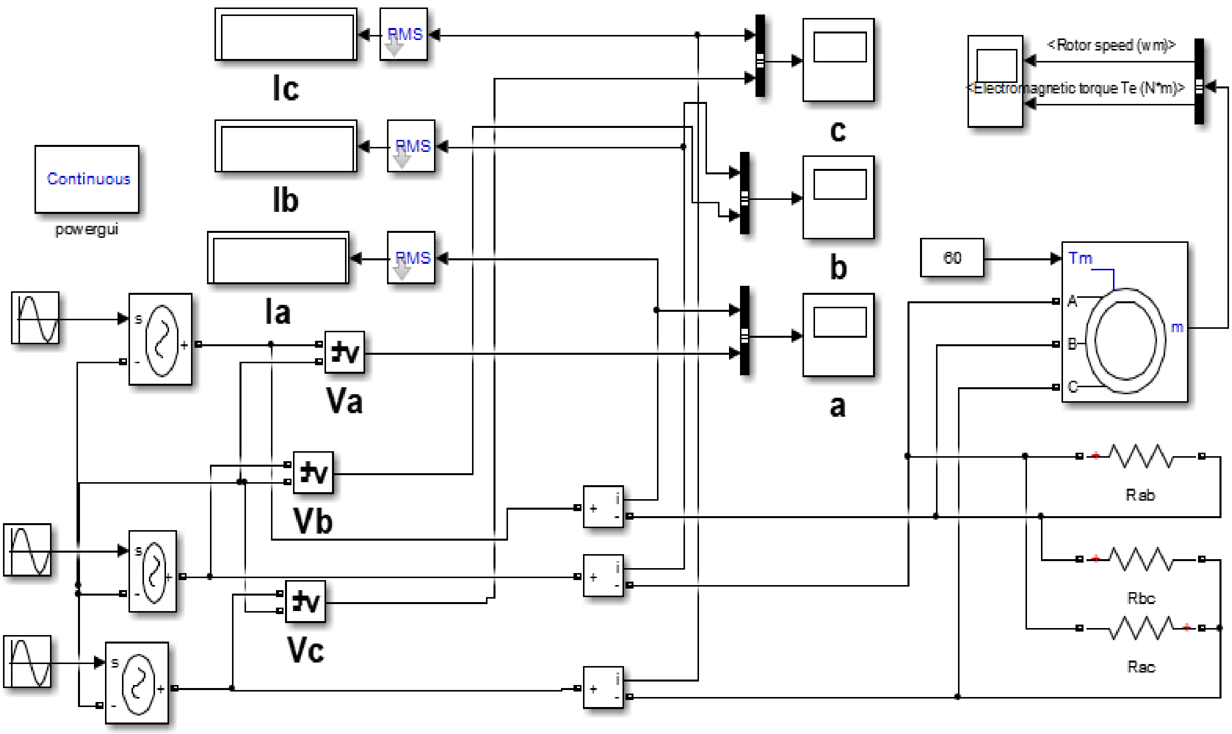

Figure 1 - Model for studying the diagnostic signs influence on the state of interfacial insulation of electric motors *(author's research)*

The measurements on the computer model were carried out under several loads, where it was determined that the dependence of the phase currents on the load is more significant than the dependence on the insulation resistance. As a result, it was assumed that the load dependence could be eliminated by determining the dependence of the leakage current on the difference between the phase currents. Figure 3 shows the obtained results of the change in phase currents depending on the resistance of the interphase insulation of the electric motor and Figure 4 shows the dependence of the difference in phase currents on the leakage current.

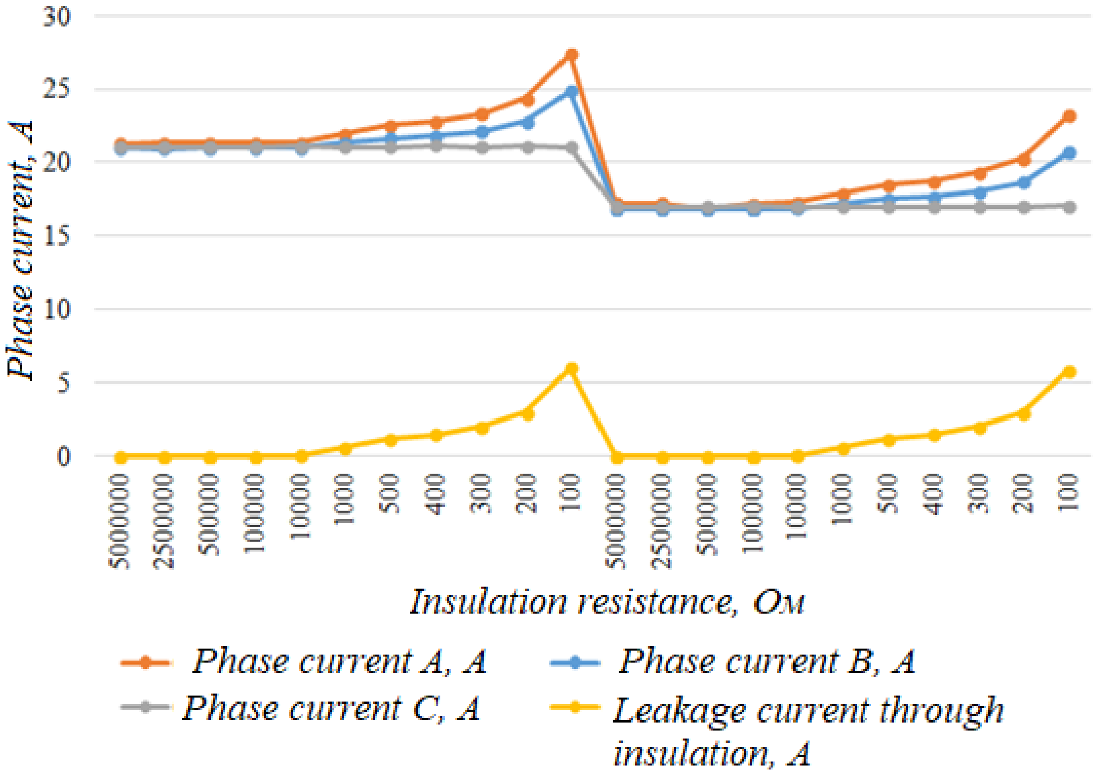

Figure 3 - Results of the study of current changes when determining the effect of insulation resistance between phases

According to the obtained results, the null hypothesis H_0 was tested regarding the absence of the influence of the identified factors on the occurrence of damage to the interfacial insulation at a significance level of $\propto = 0{,}01$ зaccording to (1)-(5). The results of studying the influence of diagnostic signs on the current state of the electric motor interfacial insulation are given in Table 1.

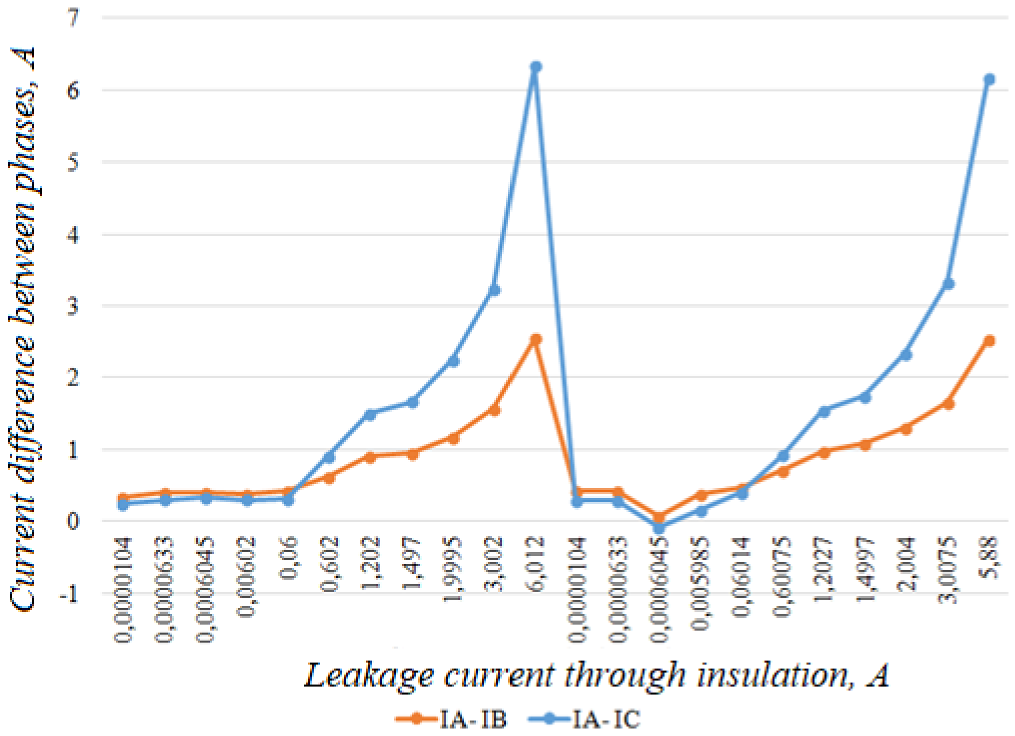

Figure 4 - Dependence of current difference between phases on leakage current

The results obtained (Table 1) show that the hypothesis H0 regarding the absence of the influence of the identified factors on the interfacial insulation in electric motors is not confirmed, since the condition $|z^*| < t_{1-\frac{\alpha}{2}}(m-2)$ is not met due to the fact that the sample value of the statistic significantly exceeds the distribution quantile *t* of the Student's criterion at the significance level α=0,01. his circumstance indicates that the leakage current through the insulation between the motor phases correlates with the differences in the currents of phases A and B and A and C and allows us to confirm the occurrence of a violation of the interphase insulation in electric motors.

Table 1 - Results of calculating critical values of correlation coefficients

Metric		r_{A-B}	r_{A-C}
correlation coefficient	*r*	0,989	0,9987
sample value of statistics	z*	29,9	87,62
is the distribution quantile t of the Students' criterion (α=0,01)	*t*	2,85	2,85
acceptance of the hypothesis H_0: r=0	yes/no	no	no

Given that a phase-to-phase insulation defect is correlated with a phase current difference, however, it can occur due to several factors, so that the phase current difference itself indicates a phase-to-phase insulation defect with a certain probability. In view of this, this probability will be defined as the ratio of one to the number of possible factors of the difference between the phase currents, which include the occurrence of a voltage difference in the power supply system; the occurrence of the insulation defect between the phases of the electric motor; the occurrence of a turnover fault in one phase of the electric motor. Thus, the probability of the difference between the phase currents caused by damage to the interphase insulation of the electric motor is equal to:

$$P\left(\frac{\Delta I}{R_{\text{Із}\text{М}\text{ф}}}\right) = \frac{N_{\text{Із}\text{М}\text{ф}}}{\sum_{i=1}^{n} N_{\Delta I}} = 0{,}33, \quad (7)$$

$P\left(\frac{\Delta I}{R_{\text{Із}\text{М}\text{ф}}}\right)$ – the probability of a difference in motor phase currents due to a decrease in interphase insulation;

$N_{\text{Із}\text{М}\text{ф}}$ – the number of factors by which the diagnosis is carried out, in our case, a defect in the interfacial insulation is diagnosed;

$N_{\text{Із}\text{М}\text{ф}}$ – the total number of factors leading to the difference in phase currents in the electric motor.

3.3. Simulation of the diagnostic features influence on the technical condition of the winding insulation of electric motors

In modern production environments, the operation of electromechanical equipment is often accompanied by such a phenomenon as a winding short circuit, which occurs as a result of a defect in the winding insulation of electric motors. Diagnosing such faults is a rather difficult process, since the short circuit of one or more turns does not significantly reduce the winding resistance, and therefore does not reflect significant changes in the phase current. However, a significant current flows in the shorted turns, which significantly reduces the inductance of the motor phase winding, resulting in a change in the phase shift between the phase voltage and phase current. The scheme for determining the parameters with which the winding short circuit correlates is shown in Figure 5.

The computer model contains a three-phase voltage source, an electric motor, and inductors connected in parallel to the motor phases. The main indicators were determined using ammeters and voltmeters connected to the circuit (Figure 5), and the phase shift was measured using the inverse trigonometric function of the ratio of active and total power. The measurement circuit (Figure 6) contains blocks for measuring phase voltage and current, a converter of the measurement result into actual values, a multiplier, a mean value determiner, a divider, and a converter of the division result into an angle measured in radians.

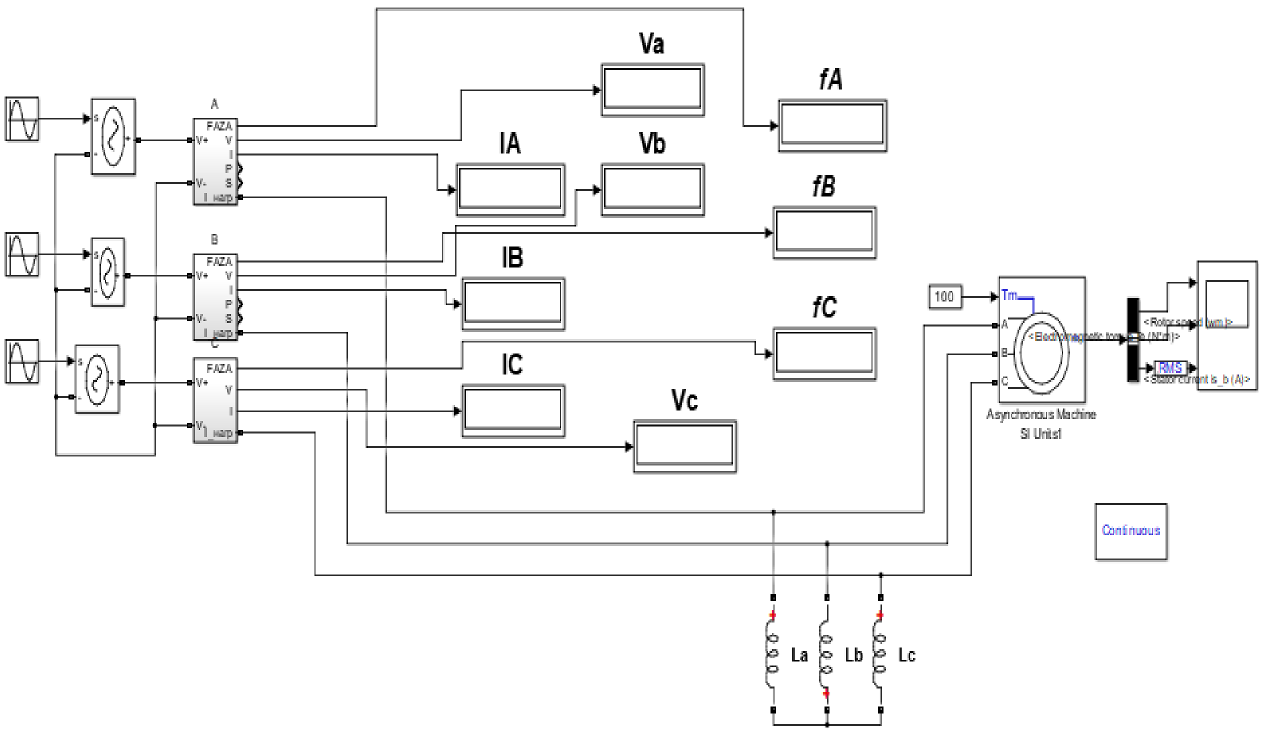

Figure 5 - Computer model for determining the parameters with which a coil circuit correlates *(author's research)*

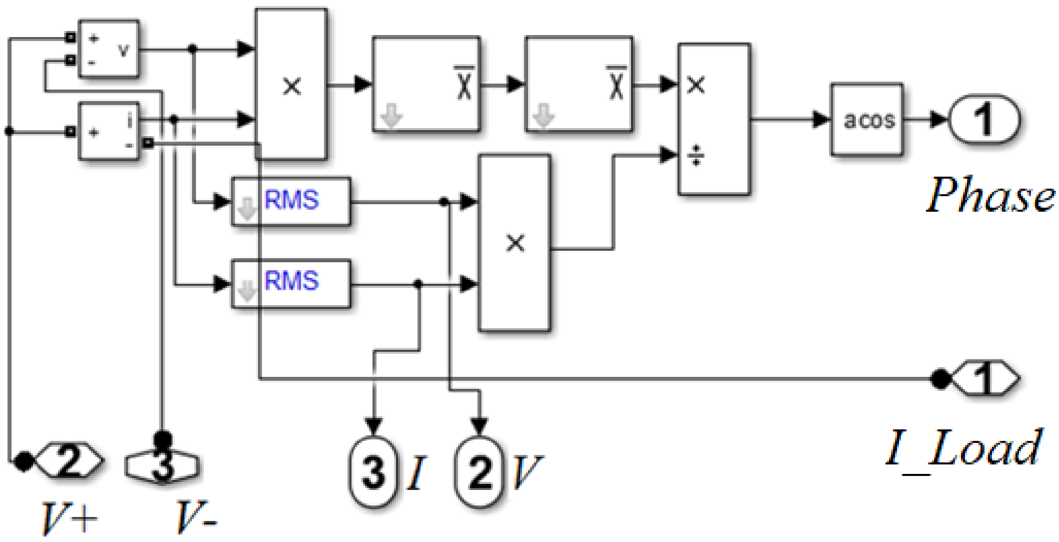

Figure 6 - Measurement scheme for the study of correlation with a coil circuit *(author's research)*

The study revealed the dependence of phase currents and phase shifts on inductance, which helped to determine the parameters with which a turnover fault can correlate (Figures 7 and 8).

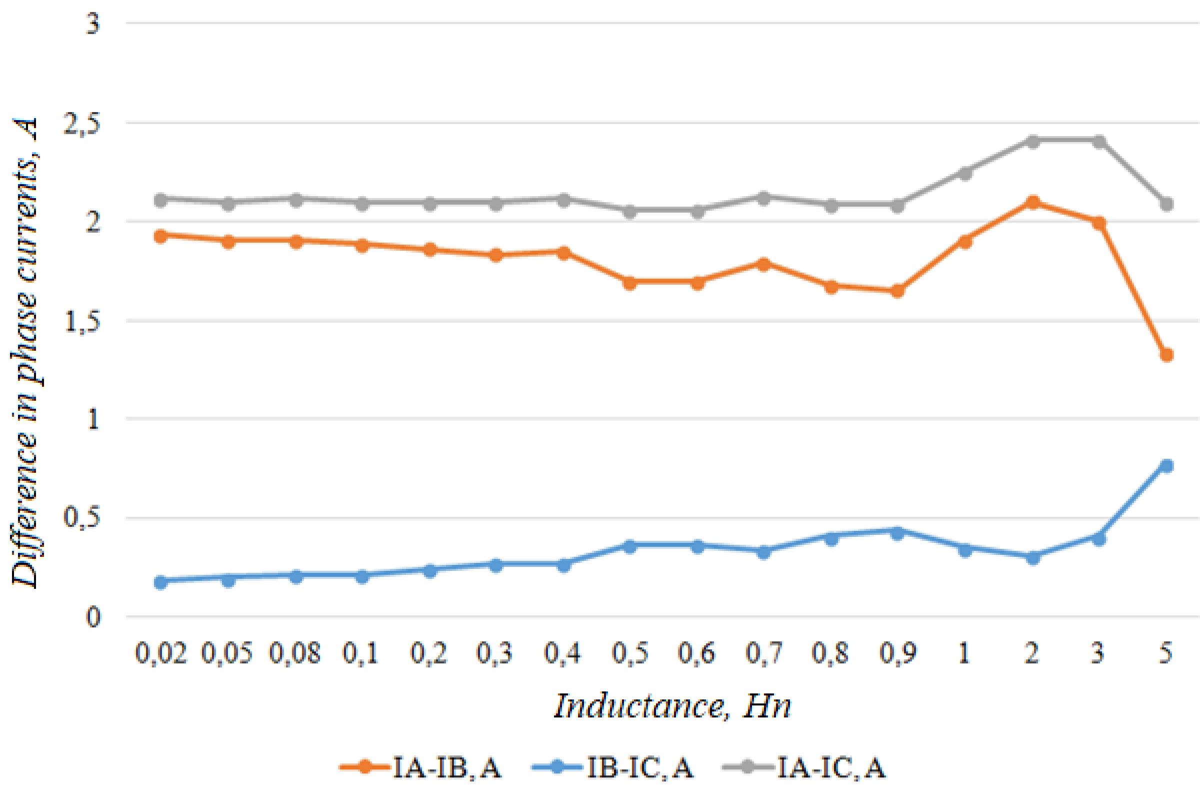

Figure 7 - Dependence of phase current difference on inductance

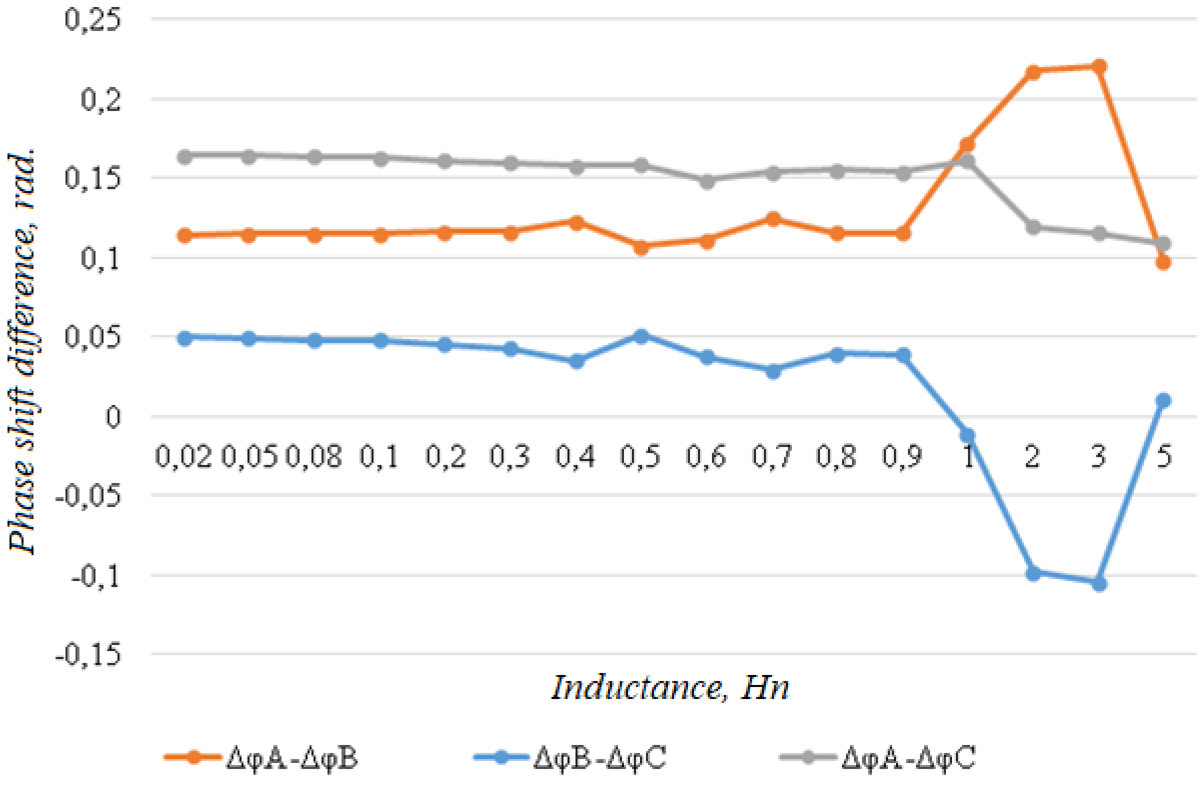

Figure 8 - Dependence of phase difference on inductance

Table 2 shows the results of studying the critical values of the correlation coefficients (1-5), which show that the hypothesis H_0 egarding the absence of the influence of the identified factors on the appearance of a defect in the twisted insulation in motors is not confirmed due to the failure to meet the specified condition $|z^*| < t_{0,995}$(14), since the sample value of the obtained statistical values significantly exceeds the distribution quantile t of the Student's criterion at the significance level α=0,01.

The results obtained show that the winding fault correlates well with the phase shift between voltage and current and significantly correlates with the difference in currents in the phases opposite to the one where the winding fault appeared, and allow us to confirm the occurrence of a violation of the winding insulation in phases A and B of electric motors.

Taking into account the above, the violation of the winding insulation, which is a consequence of a decrease in its resistance and a change in the inductance of the motor phase, correlates with the difference in phase shift between current and voltage for

Table 2 - Results of the study of critical values of correlation coefficients

Metric		I_A-I_B, A	I_B-I_C, A	I_A-I_C, A	$\Delta\varphi_A$-$\Delta\varphi_B$, rad.	$\Delta\varphi_B$-$\Delta\varphi_C$, rad.	$\Delta\varphi_A$-$\Delta\varphi_C$, rad.
correlation coefficient	r	-0,44	0,87	0,42	0,33	-0,59	-0,93
sample value of statistics	z*	-1,833	6,602	1,732	1,308	-2,734	-9,467
is the distribution quantile t of the Students' criterion (α=0,01)	t	2,977	2,977	2,977	2,977	2,977	2,977
acceptance of the hypothesis H_0: r=0	yes/no	yes	no	yes	yes	yes	no

different phases and with the difference in phase currents. In view of this, it is accepted that the difference in phase shift between current and voltage can be caused by the following circumstances: firstly, by a defect in the insulation between the phases, and secondly, by an uneven phase shift from the voltage source to which the motor is connected. It follows that the probability that a phase shift difference indicates an insulation defect is as follows:

$$P\left(\frac{\Delta\varphi_{\text{дв}}}{R_{\text{вит.із.дв}}}\right) = \frac{N_{\text{вит.із.дв}}}{\sum_{i=1}^{n} N_{\Delta\varphi_{\text{дв}}}} = \frac{1}{2} = 0{,}5, \tag{8}$$

$\Delta\varphi_{\text{дв}}$ - electric motor phase difference;

$R_{\text{вит.із.дв}}$ - resistance of the motor winding insulation;

$N_{\text{вит.із.дв}}$ - the number of factors to be diagnosed, in this case, an insulation defect between phases is diagnosed;

$\sum_{i=1}^{n} N_{\Delta\varphi_{\text{дв}}}$ - the total number of factors that lead to the occurrence of a phase shift difference between current and voltage.

The probability that the occurrence of these phenomena in the aggregate, that is the current difference and the phase difference, will indicate the presence of a defect in the twisted-coil insulation is determined as the sum of the combined probabilities:

$$P\left(R_{\text{вит.із.дв}}\right) = P\left(\frac{\Delta I}{R_{\text{вит.із.дв}}}\right) + P\left(\frac{\Delta\varphi_{\text{дв}}}{R_{\text{вит.із.дв}}}\right) - P\left(\frac{\Delta I}{R_{\text{вит.із.дв}}}\right) \times P\left(\frac{\Delta\varphi_{\text{дв}}}{R_{\text{вит.із.дв}}}\right) =$$

$$= 0{,}5 + 0{,}5 - 0{,}5 \times 0{,}5 = 0{,}55, \qquad (9)$$

Conclusions

Simulation models of measuring phase currents as a function of insulation leakage current are proposed to determine the dependencies between the leakage current through the interphase insulation and phase currents and to determine the parameters with which the winding defect correlates. A functional analysis of the factors influencing the occurrence of defects in the winding and interphase insulation of electric motors was carried out and the probability of their failure in the event of such defects was determined. It was found that high values of the correlation coefficients indicate a functional connection between the leakage current through the interphase insulation and the phase currents, as well as between the phase shift of current and voltage and the winding insulation of electric motors. It was found that for electric motors, the probability of interphase insulation defects in the presence of a difference in phase currents is about 0.33, and the probability of defects in the winding insulation in the presence of a difference in phase currents and a difference in phase shifts between current and voltage is close to 0.75. The obtained results can be used in the development of models of diagnostic systems for monitoring the condition and prevention of insulation damage and preventing emergencies associated with its violations.

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Chapter 3.

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Chapter 4.

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