

UDC 621.3

**Yuriy Dubravin<sup>1\*</sup>, Yaroslav Shostak<sup>2</sup>, Vitaly Bakhonya<sup>3</sup>, Viktor Tkachenko<sup>4</sup>**

<sup>1</sup>Associate professor, Electromechanics and Railway Rolling Stock Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine. ORCID: <https://orcid.org/0000-0001-9006-5198>

<sup>2</sup>Postgraduate student, Electromechanics and Railway Rolling Stock Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine. ORCID: <https://orcid.org/0009-0006-2886-3264>.

<sup>3</sup>Postgraduate student, Electromechanics and Railway Rolling Stock Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine. ORCID: <https://orcid.org/0009-0007-5753-2138>.

<sup>4</sup>Professor, Electromechanics and Railway Rolling Stock Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine. ORCID: <http://orcid.org/0000-0002-5513-2436>

\*Corresponding author: [dubravin\\_yf@gsuite.duit.edu.ua](mailto:dubravin_yf@gsuite.duit.edu.ua)

### **Justification of choice of methods for diagnostics of insulation condition of electrical machines of electric railway stock**

*The object of the study is the process of monitoring the technical condition of electrical insulation of traction electric machines in order to determine the need for their maintenance or repair. Diagnostics of electric machines is an important aspect of supporting the operation of electric drives. Failure of the windings is one of the main reasons for failure of electric motors. Therefore, the task of developing operational methods for diagnosing the insulation of windings of traction electric motors is urgent. A study of the negative impact of operating conditions on the technical condition of electrical insulation of motors was carried out. The analysis of the existing methods of diagnosis of insulation systems of electric machines was carried out. Special attention was paid to the selection of predictive parameters of the insulation state. A mathematical model was developed to study the frequency characteristics of the stator insulation system of the traction electric motor model AD914. Refined dependences of the effect of changes in the insulation parameters of the motor stator winding on its frequency characteristics were obtained. It was concluded that the method of monitoring the insulation state of electric motor windings based on the assessment of electrical resistance relative to the stator core and amplitude-frequency characteristics is the most effective. The field of practical application of the obtained results is the system for monitoring the condition of electrical insulation of traction electric machines to determine the schedule of their maintenance and repair. The conducted research is a scientific justification for the choice of methods and devices for diagnosing the insulation state of electric motors of railway traction rolling stock.*

**Keywords:** *diagnostics, mathematical model, electrical insulation, damage, amplitude-frequency characteristic*

**Introduction.** The stability of the insulation characteristics of electric machines is one of the main factors that guarantee the reliability of the traction electric drive of locomotives and electric trains. The problem of the stability of the technical condition of the electric motors of locomotives and electric trains is becoming more and more acute, which is explained by the following objective reasons: a long period of operation, which leads to aging of the insulation material; deterioration of the voltage quality in the power supply network due to the emission of high-frequency harmonics; increase in traffic speeds, etc.

Analysis of cases of failure of traction rolling stock and linear equipment during the warranty period of operation for the period of January 2021. – December 2022 indicates a steady trend of growth in the number of refusals. Thus, during 2022, the number of failures of traction rolling stock and its equipment as a whole in the locomotive industry of JSC "Ukrzaliznytsia" increased from 34 to 85 cases. Moreover, 25% of the total number of failures of traction motors is due to damage (breakdown) of electrical insulation. The failure mechanism of asynchronous motors depends on various parts, the most important of which is the stator winding. At the same time, the main cause of failures of auxiliary alternating current machines (AE-92-4 asynchronous electric motors, RF-1 splitters) is insulation breakdown of the stator windings, which accounts for up to 85% of the total number of failures of the specified type of machines. Failures of DC traction motors (NB-418, RT-51) in 60% of cases are associated with insulation breakdown of the armature windings, main and additional poles.

In the operation process of electric machines of locomotives and electric trains, the insulation is under the influence of electrical, mechanical, climatic and physico-chemical factors. The results of the operation show that the deterioration of the insulation is primarily due to the nature of the load. Frequent starts of machines under load, which are accompanied by significant starting currents and electrodynamic forces. Under the influence of these efforts, cracks appear in the insulation, which contribute to the further development of defects.

Vibration, cyclic temperature changes of the windings – heating during operation and cooling after operation – create thermomechanical stresses in the insulation system, contribute to the formation of condensate and moistening of the insulation. The combined effect of the listed factors leads to irreversible physicochemical processes in the structure of the insulation, which deteriorates over time, that is, to its aging, which is expressed in drying, evaporation of volatile components, loss of elasticity, the appearance of pores and cracks and their filling with moisture due to condensate. In addition, in the process of manufacture or repair, damage to the inter-turn insulation, gas inclusions after the process of impregnation of the windings, which reduces the breakdown inter-turn voltage, may be allowed. Contamination and deposition of dust with metal impurities can create a conductive layer on the insulation of the windings. Around this layer, the electric field increases, which can lead to insulation damage due to partial discharge.

Analysis of the causes of failure of electric machines shows that the main cause of damage to the stator winding is a short circuit between the turns, which is accompanied by overheating of the short-circuited sections of the turns. If an inter-turn short circuit is not detected and eliminated in time, an inter-phase short circuit or a breakdown of the machine body may occur.

**2. Literature review and problem statement.** Currently, considerable attention is paid to the development of methods for detecting and diagnosing electrical faults in three-phase asynchronous motors, especially failures occurring in the stator winding.

The work [1] indicated a high probability of insulation breakdown in the stator winding due to overload, aging and mechanical vibrations. Therefore, it is necessary to use a reliable toolkit to detect the degradation of electrical insulation of electric motors in order to avoid any potential consequences.

The article [2] gives an overview of the existing methods of diagnosing the technical condition of insulation of electrical machines. These methods are organized according to the type of tests performed. The issue of operational supervision, maintenance and diagnostics of insulation systems of electric machines is discussed. The negative influence of operating conditions and various factors on the technical condition of the insulation system is described. Special attention is paid to the review of available methods of diagnosis of insulation systems of electric machines and their systematization according to the type of tests.

In work [3], an analysis of the methods of diagnosing electric machines, types of defects, as well as means for their detection during production and operation was carried out. The work provides an opportunity to evaluate the effectiveness of the analyzed methods and predict the future development of diagnostic methods.

More and more attention is paid to the design of new insulation materials and insulation systems. The article [4] discusses the latest achievements in the field of insulation systems of electric machines.

Two categories of electrical insulation tests are considered: online tests; testing in off-line mode. Test standards and methods for detecting insulation damage are given. A study of developing technologies was conducted. The effect of partial discharges on insulation systems was discussed.

The article [5] discusses practical approaches to detecting single-turn short circuits. It is emphasized that this type of short circuit belongs to the most serious type of insulation damage, when the inductance of the winding decreases and the circulating current increases. In the work, it is proposed to use the method of high-frequency signal supply to the windings of the electric machine and its analysis for reliable online diagnostics of malfunctions. The obtained results of the experiments confirm the effectiveness of the proposed method.

According to the study [6], existing and potential methods for diagnosing the insulation of electric machines should include the following partial discharge tests; insulation resistance tests between the coil and the core and dielectric spectroscopy. Dielectric spectroscopy is possible in the time and frequency domain. A partial discharge test can reveal insulation defects between turns, between phases and earth. For example, voids, cracks and delamination in the insulation, as well as degradation of the insulation of its chemical composition.

In [7], a new approach to monitoring partial discharge test data based on the condition index is proposed. The types of partial discharge, equipment for substantiating the maintenance schedule and the need for repair are considered. The issue of detecting partial discharges and reducing their negative consequences is discussed in works [8–10].

The work [11] presents a developed methodology for determining the type of malfunction and the location of damage by analyzing the amplitude-frequency characteristic. It is noted that it is necessary to conduct a number of measurements to form a database of frequency characteristics. The expediency of using the method of amplitude-frequency characteristics as a diagnostic tool for detecting internal malfunctions in asynchronous motors is also evidenced by the results of experiments given in works [12, 13].

Using the method of amplitude-frequency characteristics, it is possible to evaluate the mechanical integrity of the winding inside the machine, detect broken tires, broken rods in short-circuited rotors of asynchronous motors, and obtain a comprehensive assessment of the state of the bearings of the rotor shaft [14–16].

The results of the studies presented in [17, 18] show the high accuracy of the method of amplitude-frequency characteristics for detecting short circuits in the windings of asynchronous motors. In particular, in [18] the application of the method of amplitude-frequency characteristics in the online mode is proposed.

In [19], the insulation test with voltage pulses, which is applied between the winding and the machine body during the production and overhaul of asynchronous motors, is considered for diagnostic purposes and is used as a comparative method. The method of impulse tests is also considered in [20]. The method consists in disconnecting the charged capacitor from the winding and recording the transient process in the winding circuit. On the basis of the created mathematical model of switching processes in the windings of electric machines, a diagnostic system for assessing the quality of insulation of the windings is proposed based on multi-physical processes that occur when the current breaks in the windings of electric machines.

The method of high-frequency capacitance impedance is also used to monitor the deterioration of the insulation condition of electric motor coils. Periodic measurements of partial discharges, dielectric losses and capacitance, as shown in [21], are the most effective for assessing the phenomenon of insulation aging.

The article [22] presents the results of experimental research on the dependence of thermal, mechanical and electrical changes in capacitance and the dielectric loss angle on aging time and applied voltage.

The above analysis of well-known information sources on this topic allows to assert the feasibility and prospects of improving the methods of diagnosing electric machines by modifying tests, improving

the effectiveness of predictive parameters, optimizing diagnostic periods, and expanding online testing based on the use of modern sensors and modern digital signal processing algorithms.

**The aim and objectives of the study.** The aim of the study is the development of methods for diagnosing the state of electrical insulation of traction electric motors of electric locomotives and electric trains. The main tasks of the study are as follows: the study of the possibility of using the impedance of the insulation capacity as a test for monitoring the insulation state; improvement of the method of detecting insulation defects based on the use of impulse diagnostic methods; comparison of the accuracy and efficiency of the amplitude-frequency and impulse methods of monitoring the insulation state.

**Materials and methods of the study.** It is accepted that the condition of the electrical insulation of electric motors is determined using diagnostic tests that allow to assess the degradation degree of the insulation caused by aging. Two categories of electrical insulation tests are considered: on-line tests and off-line tests. Testing by the method of partial discharge in real time is performed at a frequency of 50 Hz in the stator windings with a nominal voltage of 2 kV and above according to the "phase-earth" scheme on one phase simultaneously with the grounding of the other two phases. Partial discharge is one of the main factors that can lead to insulation damage. It usually appears in voids, pores between the insulating material, inside or on the surface of the insulating system and is characterized by spark impulses that lead to heating of the insulation. Due to their repetition, partial discharges create conditions for insulation breakdown. The list of parameters by which the insulation state can be evaluated, the reasons for their deterioration, which lead to a decrease in the reliability of electric machines, is considered. Tests that make it possible to detect malfunctions in the windings and timely prevent failures of electric machines in operation are considered.

#### Research results.

**Study of parameters characterizing the insulation state.** The most important parameter that must be monitored and which helps to check the condition of the electrical insulation is the electrical resistance of the insulation. The resistance is estimated by the current flowing in the insulation circuit when the voltage is applied. The flowing current includes polarization current, through current and surface conduction current. However, measuring resistance does not give a complete picture of the insulation state. The absolute value of the resistance is an integral characteristic that is insensitive to local changes in its value, which most often lead to a breakdown. The polarization index test consists of testing the insulation between phase and earth with a high DC potential. The method allows to detect and localize pollution, the main defects in the insulation and is a sensitive indicator of the presence of moisture in the winding.

The equivalent model of replacing the insulation of individual coils of an electric machine, as a type of solid dielectric, can be simplified in the form of a parallel replacement scheme (Fig. 1). The parallel substitution circuit can be considered as a dielectric model, in which the elastic polarization current is modeled by the capacitance  $C$ , and the electrical conductivity by the resistive resistance  $R$ . The current caused by the polarization processes of displacement of bound charges in the dielectric takes place in the presence of an alternating electric field. Polarization of the dielectric under the influence of an alternating electric field causes losses of active electric power – dielectric losses that are released as heat in the dielectric and cause heating of the insulation. Dielectric losses are characterized by the dielectric loss angle tangent  $\operatorname{tg}\delta$ , that is, the ratio of the intensity of the real component  $I_R$  to the imaginary component  $I_C$  of the electric current flowing through the dielectric in an alternating electric field.

The vector of the total current  $I$  is obtained by adding the vectors of the active  $I_R$  and reactive  $I_C$  currents, the ratio of which in the right-angled triangle of currents gives the dielectric loss angle tangent  $\operatorname{tg}\delta = I_R/I_C = 1/(\omega \cdot R \cdot C)$ , where the angular frequency is  $\omega = 2 \cdot \pi \cdot f$ ,  $\text{s}^{-1}$ . The value of the capacitance  $C$  between the stator conductors and the grounded core can be a parameter that characterizes thermal wear, moisture absorption and contamination of the winding. Tracing the trend over time of the dielectric loss angle tangent  $\operatorname{tg}\delta$  can provide a general idea of the dielectric loss and the general condition of the stator insulation.



Fig. 1. Model of replacing the insulation of an electric machine

The ability of the dielectric to polarize characterizes the relative dielectric constant, however,  $tg\delta$  is a more sensitive characteristic for diagnosing the technical condition of the electrical insulation of electrical equipment than the relative dielectric constant, because it changes within wider limits when external factors change. A change in the  $tg\delta$  value during operation allows to judge the drying, wetting and damage of the electrical insulation, the appearance of cracks and the loss of plasticizer.

The results of experiments [22] show that, regardless of the type and strength of the voltage, the insulation characteristics deteriorate with aging. At the same time, the capacity  $C$  and  $tg\delta$  increases. Long-term thermal stresses lead to an increase in  $tg\delta$ , and the breakdown voltage is significantly reduced in the case of combined electrical and mechanical stresses due to the presence of defects.

Dielectric losses represent the sum of conduction losses and polarization losses, that is, losses due to the occurrence of a partial discharge. If there are voids or cracks in the insulation, and the magnitude of the electric field is lower than the dielectric strength of air, the ionization process will not occur. As long as the voids of the insulation are not ionized, the value  $tg\delta$  will depend only on the loss coefficient of solid particles  $tg\delta = tg\delta_s$  [21]. In this case, the measured value  $tg\delta$  is only slightly affected by the applied voltage. When the electric field strength of the air increases, the void begins to ionize (partial discharges occur), the parameter will increase sharply with the applied voltage. Measuring the dielectric loss of the insulation of a three-phase electric machine involves testing each winding in turn. When measuring, a 50 Hz alternating sinusoidal voltage is applied between the phase winding and ground, and the other two phases are grounded to the stator core.

**Diagnostic methods.** Existing and promising diagnostic methods include on-line and off-line testing. In the on-line mode, the technical condition of the insulation system can be determined using continuous monitoring of the electric machine. For this, measurements of various physical quantities are used: magnetic flux; temperature; stator winding current. The most common types of on-line insulation testing include: thermal monitoring; partial discharge test; current spectral analysis and overvoltage monitoring. On-line tests are carried out during operation of the electric machine. However, only with the help of online monitoring, it is impossible to detect all malfunctions of an electric machine. Therefore, off-line tests are necessary, during which the electric machine is disconnected from the network and testing methods are applied. The disadvantage of the on-line monitoring method is the need to install additional equipment at each machine monitoring object. Compared to off-line testing, some insulation defects are more difficult to detect. Further development of diagnostic methods, hardware and monitoring algorithms will undoubtedly make it possible to expand the scope of application of the online monitoring method.

The method of high-voltage impulse tests is one of the effective methods of assessing the insulation state of machine windings. This method is comparative. It consists in connecting the test voltage of the charged capacitor between the winding and the magnetic circuit and recording the current discharge or voltage drop on the winding. Deterioration of the insulation affects the high-frequency behavior of the machine. This is the basis of the condition monitoring method, which allows detecting changes in the insulation by estimating the transient current when the pulse is applied.

Depending on the parameters of the circuit, the process of changing the voltage on the winding has an oscillatory or aperiodic damping character. The resulting oscillogram of the transient process is compared with the previously recorded oscillogram (for a working or new winding) and on this basis the deterioration of the winding insulation is assessed. Any anomaly in the insulation system of the windings is manifested by a change in the frequency and decrement of the attenuation of the evanescent wave. Analysis of time oscillograms allows to quickly and easily determine the state of inter-turn insulation. This makes it possible to detect both short circuits and deterioration of the insulation between individual turns, as well as between winding coils.

Another method that is similar to the high voltage pulse method is the DC off method. The research methodology consists in supplying the tested circuit with a direct current, the value of which is much lower than the rated current of the tested machine. Measurements can be made on the windings connected together, or on the windings of each phase separately. The technical condition of the insulation of the windings is assessed based on the analysis of the voltage parameters generated at the winding terminals. Based on the analysis, the following values are compared: the frequency of the induced voltage; the shape of the induced voltage and the logarithmic damping factor.

One of the most common methods for diagnosing electrical machines and transformers is the dielectric spectroscopy (DS) method, which can be considered in both the time and frequency domains. In the time domain, the method includes measurement of current, capacitance, and dielectric loss angle tangent. DS in the frequency domain mainly involves the analysis of the amplitude-frequency response (FRA). Frequency Response Analysis (FRA) consists in calculating the impedance of the winding over a wide frequency range and comparing it with a reference set.

The FRA method is based on the fact that the electrical circuit of the stator and rotor is equivalent to an electrical network consisting of active resistance, capacitance and inductance, which has its own unique frequency response. The FRA test is used to diagnose inter-turn faults in coils during the repair of an electric machine and during its operation. In order to determine the sensitivity and effectiveness of the frequency testing method for assessing the insulation state and localization of defects, the transfer function of the winding insulation system is considered in the work.

**Results of traction motor insulation research.** When performing capacitance tests,  $\text{tg}\delta$  or polarization index, it is desirable to measure each phase separately under the same conditions to monitor changes over time in the parameters of each phase and to compare values between phases. A mathematical model was created in the Matlab-Simulink software environment to conduct research on insulation parameters of electrical machine windings. In the model, each winding of an asynchronous machine is considered taking into account its inductance  $L$ , phase capacitance  $C_f$ , distributed transverse capacitance relative to the stator  $C_n$  and insulation resistance  $R$  relative to the stator (Fig. 2).

Capacitance  $C_n$  and dielectric loss of insulation between the phase winding and the case will be obtained from experiment XX (Fig. 1) when the winding terminals are closed ( $C_f=0$ ;  $L=0$ ) and the alternating voltage  $U$  with a frequency of 50 Hz is applied to the phase.

Complex of the total winding leakage current

$$I = U \cdot Y, \quad (1)$$

where  $Y = \sqrt{G^2 + B_c^2} = G + e^{j\frac{\pi}{2}} \cdot B_c \cdot Y$  – complex conductivity;

$G=1/R$  – active conduction;

$e^{j\frac{\pi}{2}} \cdot B_c = e^{j\frac{\pi}{2}} \cdot \omega \cdot C_n$  – capacitive conductivity complex.

With known values of applied voltage  $U$ , leakage current  $I_R$  and total current  $I_\Sigma$ , let's obtain:

$$Y = \frac{I_\Sigma}{U}; \quad G = \frac{1}{R}; \quad B_c = \sqrt{Y^2 - G^2} = \omega \cdot C_n.$$

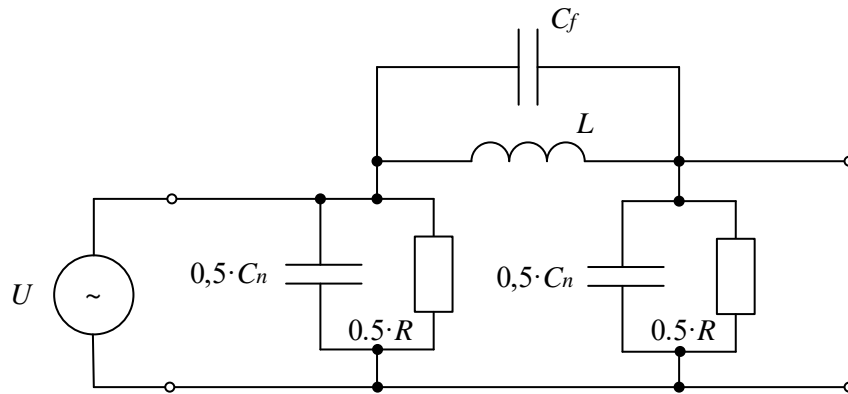


Fig. 2. Simplified model of insulation of one winding of an electric machine

From the last expression, the winding capacity is distributed:  $C_n=1/(X_C \cdot \omega)$ .

Reactive current  $I_C=B_C \cdot U$ .

Dielectric losses of active power are obtained from the ratio of active current and reactive current, or the resistor conductivity  $1/R$  to the reactive conductivity:

$$\frac{\omega \cdot C_n}{\text{tg} \delta} = \frac{1}{R \cdot \omega \cdot C_n} \quad (2)$$

With the help of the model, research was carried out on the insulation of the winding of the AD914 asynchronous traction motor (Table 1).

Table 1. Input data of the AD914 asynchronous traction motor

Power at terminals $P_H$ , kW	1200
Active resistance of the stator phase $R_f$ , $\Omega$	0.0344
Total active resistance of the motor $R_\Sigma$ , $\Omega$	0.0619
Inductive resistance of the stator phase $X_L$ at a frequency of 50 Hz, $\Omega$	0.213
Short-circuit resistance $Z_k$ at a frequency of 50 Hz, $\Omega$	0.379

When applying to the stator phase an alternating voltage with a frequency of 50 Hz, the obtained calculated parameters are given in the Table 2.

Table 2. Results of calculating the parameters of traction type AD914 insulation

Reactive current $I_C$ , A	$1.192 \cdot 10^{-3}$
Active current $I_R$ , A	$1.0 \cdot 10^{-3}$
Complete current $I_\Sigma$ , A	$3.923 \cdot 10^{-3}$
Active resistance $R_2$ , $\Omega$	$1.0 \cdot 10^6$
Capacitive resistance $X_C$ , $\Omega$	$-2.6362 \cdot 10^5$
Distributed winding capacity $C_n$ , mF	$1.192 \cdot 10^3$
Dielectric loss angle tangent $\text{tg} \delta$	$0.2671 \cdot 10^{-5}$

The model of the insulation system of a three-phase alternating current electric machine when checking the insulation of the windings must take into account the capacity of each phase  $C_f$  relative to the stator core, the capacity between the phases  $C_M$  and the resistance of the insulation between the winding phases  $R_M$  and the core  $R_f$  (Fig. 3).

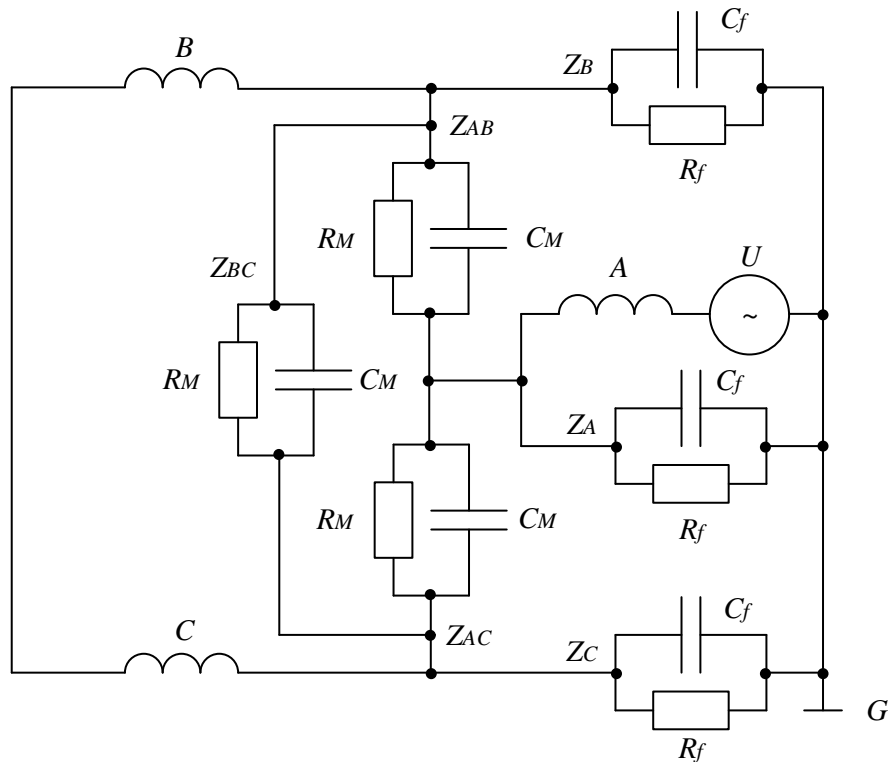


Fig. 3. A model of the insulation system of a three-phase electric machine

Impedances of windings relative to the body are marked as  $Z_A, Z_B, Z_C$  and between phases –  $Z_{AB}, Z_{AC}, Z_{BC}$ . Assuming that the insulation system of all three phases is balanced, and their impedances are equal to each other:

$$Z_A = Z_B = Z_C = Z_f; \tag{3}$$

$$Z_{AB} = Z_{AC} = Z_{BC} = Z_{MF}. \tag{4}$$

Here, the impedances of each parallel  $R$ - $C$  model between phase insulation are  $Z_{MF}$ , and the insulation of each phase relative to the case is  $Z_{MF}$ .

Complex conductivity of insulation of one phase  $\underline{Y} = G + jB_C$ , where  $G = 1/R_\Sigma$  – active conductivity;

$B_C = \omega \cdot C_\Sigma$  – reactive conductivity.

The total active resistance of the phase insulation in accordance with the scheme of Fig. 3:

$$Z_\Sigma = \frac{R_f \cdot (R_M + R_f)}{R_M + 3 \cdot R_f}. \tag{5}$$

The total capacity of one winding, taking into account the capacity relative to the case and between the windings:

$$C_\Sigma = \frac{2 \cdot C_M \cdot C_f}{C_M + C_f} + C_f. \tag{6}$$

The analytical expression for the leakage current consists of resistive and capacitive components:

$$\underline{I} = \underline{U} \cdot \underline{Y} = G \cdot \underline{U} + j \cdot B_C \cdot \underline{U}. \quad (7)$$

The phase shift between voltage and current  $\varphi = \arctg(B_C \cdot R_\Sigma)$ , the dielectric loss angle tangent

$$\operatorname{tg} \varphi = 90^\circ - \arctg(B_C \cdot R_\Sigma). \quad (8)$$

**The results of the study of frequency characteristics.** A simplified winding scheme of one phase of an electric machine (Fig. 4) includes: active resistance  $R_M$  relative to other phases and the core; the total capacity  $C_{Mf}$  of the winding phase, taking into account the capacity between winding turns and between phases; inductance  $L$ ; resistance  $R_f$  relative to the stator core.

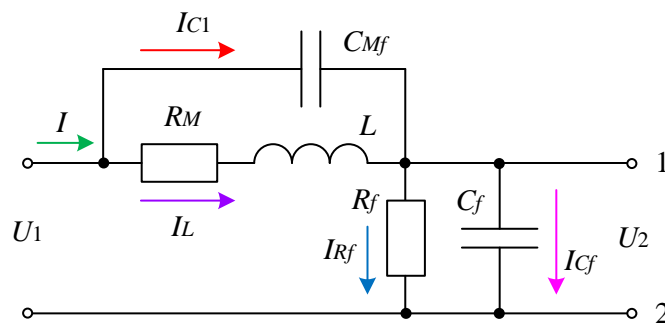


Fig. 4. A simplified winding diagram of one phase of an electric machine

The transfer function of the winding is defined as the frequency dependence of the voltage ratio at the output terminals of the winding applied to the power source. The electric circuit of the winding of the electric machine (Fig. 4) corresponds to the system of equations for the instantaneous values of the voltage drops on the elements:

$$U_1 = U_{C_{Mf}} + U_2; \quad (9)$$

$$U_{C_{Mf}} = \frac{1}{C_{Mf}} \int I_{C_{Mf}} dt = I_L \cdot R_M + L \cdot \frac{dI_L}{dt}; \quad (10)$$

$$U_2 = \frac{1}{C_f} \int I_{C_f} dt = I_{R_f} \cdot R_f \dots \quad (11)$$

The resulting system of equations provides a mathematical description of the physical processes in the winding insulation system and is the starting point for obtaining the transfer function and studying frequency characteristics. Using the direct Laplace transform, it is possible to obtain a system of algebraic equations in the images:

$$U_1(p) = \frac{1}{C_{Mf} \cdot p} \cdot I_{C_1}(p) + \frac{1}{C_f \cdot p} \cdot I_{C_f}(p); \quad (12)$$

$$U_{C_{Mf}}(p) = \frac{I_{C_{Mf}}(p)}{C_{Mf} \cdot p} = I_L(p) \cdot R_M(p) + I_L(p) \cdot L_L(p) \cdot p; \quad (13)$$

$$U_2(p) = \frac{1}{C_f \cdot p} \cdot I_{C_f}(p) = I_{R_f}(p) \cdot R_f, \quad (14)$$

where  $p$  - the Laplace operator.

Given that the total current in the circuit is  $I(p) = I_L(p) + I_{C1}(p) = I_{Cf}(p) + I_{Rf}(p)$ .

As a result of solving the system of equations (2) and a number of algebraic transformations, it is possible to obtain the dependence of the output voltage  $U_2(p)$  on the input action:

$$U_1(p) \cdot (C_{Mf} \cdot p \cdot (L \cdot p + R_M) + 1) = U_2(p) \cdot \left( C_{Mf} \cdot p \cdot (L \cdot p + R_M) + \left( C_f \cdot p + \frac{1}{R_f} \right) \cdot (L \cdot p + R_M) \right). \quad (15)$$

The transfer function of the winding insulation system is the ratio of the Laplace images of the output voltage and the input action under zero initial conditions:

$$W(p) = \frac{U_2(p)}{U_1(p)} = \frac{L \cdot C_{Mf} \cdot p^2 + C_{Mf} \cdot R_M \cdot p + 1}{(L \cdot C_{Mf} + L \cdot C_f) \cdot p^2 + (C_{Mf} \cdot R_M + C_f \cdot R_M + \frac{L}{R_f}) \cdot p + \frac{R_M}{R_f} + 1}. \quad (16)$$

The resulting transfer function includes a capacitance  $C_{Mf}$ , which is still unknown. Features of the windings of electric machines are their distributed parameters  $C_{Mf}$ ,  $L$ . The winding capacity  $C_{Mf}$  can be determined from a short-circuit test when points 1, 2 of the circuit are connected. The unknown parameter values are found through the equivalent conductivities:

$$B_C = \frac{1}{X_{C_{Mf}}}; \quad B_L = \frac{X_L}{Z_1^2}; \quad G = \frac{R_M}{Z_1^2}, \quad (17)$$

where the total resistance of the parallel branch  $R_M$ ,  $L$ :

$$Z_1 = \sqrt{R_M^2 + X_L^2}. \quad (18)$$

During resonance of currents, the phase shift between the voltage and the full current of the circuit is  $\varphi=0$ , and the condition of resonance of currents is:

$$\frac{X_L}{Z_1^2} = \frac{1}{X_{C_{Mf}}} \quad \text{or} \quad \frac{X_L}{R_M^2 + X_L^2} = \frac{1}{X_{C_{Mf}}},$$

whence the resonant frequency of the circuit:

$$\omega = \sqrt{\frac{1}{L \cdot C_{Mf}} - \frac{R_M^2}{L^2 \cdot C_{Mf}}}. \quad (19)$$

The resulting dependence makes it possible to calculate the winding capacity of one of the phases.

The following example uses the parameters of the AD914 asynchronous traction electric motor, the active resistance of the winding  $R_M$  and the inductance  $L$ , the values of which are given in Table 1. The resonance of the current took place at a frequency of  $f=5.185 \cdot 10^4$  Hz. The distributed capacity of the winding is determined from the expression (19):

$$C_{Mf} = \frac{L}{\omega^2 \cdot L^2 + R_M^2} = 1.388817 \cdot 10^{-8}, F. \quad (20)$$

Transfer function of the third-order link (16) makes it possible to analyze the frequency characteristics of the insulation system of the windings of electric machines. When investigated, it is possible to consider the system's response to a sinusoidal test signal. The output signal in this case will also be sinusoidal of the same frequency as the input signal, but differs from it in amplitude and phase. The study of frequency characteristics is significantly simplified when using logarithmic ones

The LFRA study was conducted for the stator winding insulation system of the AD914 asynchronous traction electric motor using a model.

Research was carried out for four variants of transfer functions:

$W_1$  – no insulation defects;  $W_2$  – insulation resistance relative to the stator 1 k $\Omega$ ;  $W_3$  – inter-turn short circuit;  $W_4$  – phase-to-phase short circuit.

Different types of stator winding insulation faults were specified by changing the parameters  $L$ ,  $R_M$ ,  $C_{Mf}$ ,  $C_f$ ,  $R_f$  for the corresponding transfer functions. LFRA configurations for the specified options are shown in Fig. 5.

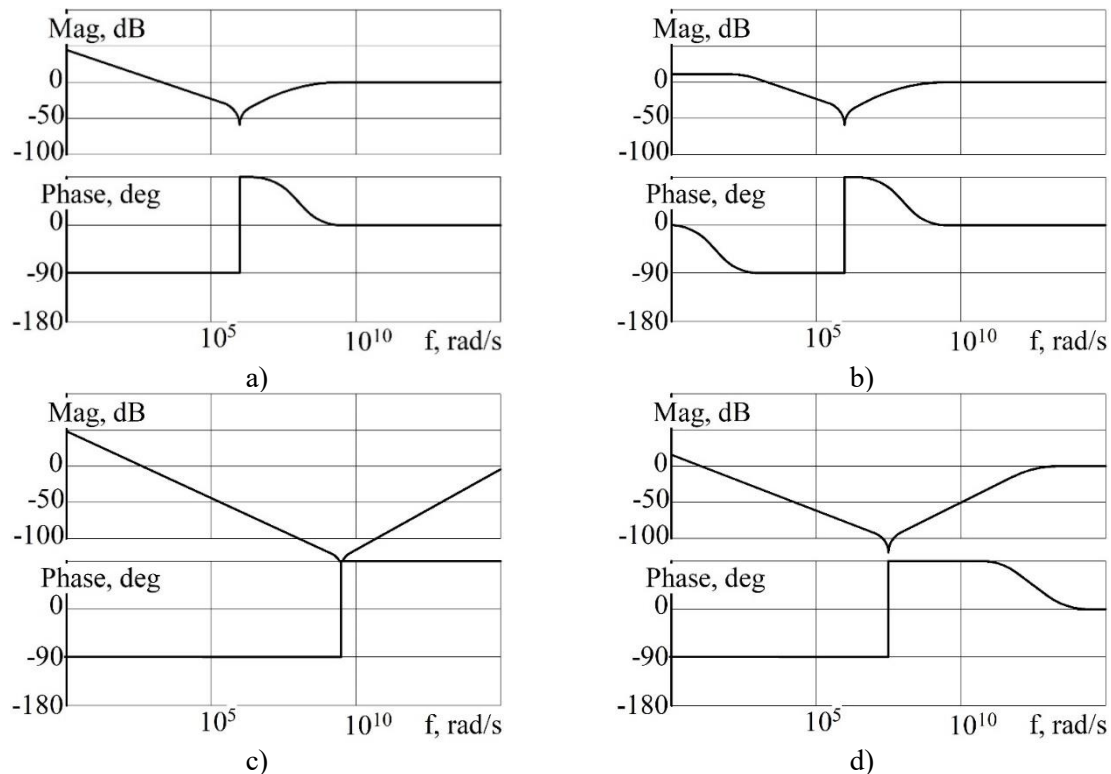


Fig. 5. Logarithmic frequency characteristics of the insulation system of the stator winding of the AD914 asynchronous traction electric motor: a) reference LFRA – no insulation defects; b) reduction of insulation resistance relative to the stator core to 1 k $\Omega$ ; c) inter-turn short circuits of phase sections; d) short circuit between winding phases.

The results of the LFRA simulation in comparison with the reference LFRA signature (Fig. 5, b) show that when the insulation resistance relative to the stator core is reduced to  $1 \text{ k}\Omega$ , a decrease in the amplitude of the frequency response in the low-frequency range from 50 to 20 Db is observed. The phase response has no initial shift at low frequencies. When the frequency increases, the shift goes towards the value  $-90^\circ$ . The resonant frequency remains unchanged.

Fig. 5, c shows that the winding circuit between the phase sections sharply shifts the resonance frequency to the right from the mid-frequency to the high-frequency range. The phase characteristic in the high-frequency range has a constant phase shift by  $+90^\circ$ . Short circuit between phases of the winding (Fig. 5d) affects the LFRA signature in the same way as the effect of turn-to-turn short circuits, but slightly reduces the frequency of the resonance point. It can be seen that when the winding is shorted between phases, the phase characteristic has a phase shift  $0^\circ$  in a higher frequency range.

The phase lock shows the largest change in the LFRA signal due to the change in the inductance of the winding circuit. When short circuit between the phases of the winding, the assumption was made that there were no interturn short circuits in the phase windings.

The obtained results indicate that the deterioration of the insulation leads to a change in the frequency characteristics of the electric motor. The LFRA signature depends on the value of all the capacitances, inductances and resistances of the windings relative to the stator core. The presence of a set of typical LFRA or FRA signatures, which are unique for different types of damage, will make it possible to use the frequency diagnostic method to detect and locate faults in the windings of rotating electrical machines.

**Conclusions.** Conducted research and modeling of malfunctions in the stator winding of the traction motor show that the most promising methods for diagnosing the insulation of electric machines of electric locomotives and electric trains are the method of amplitude-frequency characteristics and the method of insulation resistance. Diagnosing insulation during manufacturing and monitoring its condition during operation using these methods will make it possible to ensure the required level of reliability. The method of amplitude-frequency characteristics is the simplest and most reliable and makes it possible to control the dynamics of insulation parameters, localize the location and type of damage. The oscillograms of Figures 5 (a-d) show that each type of insulation damage corresponds to a certain frequency response signature with a shift in resonant frequency and amplitude. If the insulation is damaged, there is a sudden shift in the resonant frequency caused by thermal effects and aging of the insulation. The method of amplitude-frequency characteristics is the cheapest and safest alternative to the standard overvoltage test. The method of amplitude-frequency characteristics, due to the ability to detect various types of malfunctions and the lack of influence on the normal operation of the machine, can be used as a method of continuous on-line monitoring of the insulation condition of electrical machines. The method contributes to the timely assessment of the state of the insulation and makes it possible to protect the windings from further aging and avoid unexpected downtime thanks to scheduled maintenance. In further research, it is planned to conduct experimental studies of the insulation of electrical machines of electric rolling stock, select the most informative diagnostic parameters of the insulation state of specific machines, and study the dynamics of these parameters during operation.

## References

1. Sadeghi, R., Samet, H., & Ghanbari, T. (2018). Detection of Stator Short-Circuit Faults in Induction Motors Using the Concept of Instantaneous Frequency. *IEEE Transactions on Industrial Informatics*, 15(8), 4506–4515. <https://doi.org/10.1109/TII.2018.2881921>.
2. Deckner, A., Baranski, M., Jarek, T., & Berhausen, S. (2022). Methods for diagnosing winding insulation of electrical machine windings. *Energia*, 15 (22), 8465. <https://doi.org/10.3390/en15228465>.
3. Reshetniak, I. S., Falendysh, A. P., & Zinkivskyi, A. M. (2014). Pidvyshchennia nadiinosti roboty tiahovykh elektrodvyhuniv isnuichykh lokomotyviv. [Increasing the reliability of traction electric motors of existing locomotives.]. *Zbirnyk naukovykh prats Ukrainskoi derzhavnoi akademii zaliznychnoho transport - Collection of scientific works of the Ukrainian State Academy of Railway Transport*, (147), 77–82. <http://surl.li/tbtah>. [in Ukrainian].

4. Hemmati, R., Wu, F., & El-Refaie, A. (2019, May). Survey of insulation systems in electrical machines. In *2019 IEEE International Electric Machines & Drives Conference (IEMDC)*. 2069–2076. <https://doi.org/10.1109/IEMDC.2019.8785099>.
5. Wu, F., El-Refaie, A. M., & Zheng, P. (2019). Diagnosis and remediation of single-turn short circuit in a multiphase FSCW PM machine based on T-type equivalent circuit. *IEEE Transactions on Industry Applications*, 56(1), 158–169. <https://doi.org/10.1109/TIA.2019.2946525>.
6. Hemmati, R., Wu, F., & EL-Refaie, A. (2019). Survey of Insulation Systems in Electrical Machines. *Electrical and Computer Engineering Faculty Research and Publications*. 537. <https://doi.org/10.1109/IEMDC.2019.8785099>.
7. Montanari, G. C., Seri, P., & Contin, A. (2018, June). How to deal with the severity of different partial discharge sources in rotating machines: the definition of a new health index. In *2018 IEEE Electrical Insulation Conference (EIC)*. 469–472. <https://doi.org/10.1109/EIC.2018.8481118>.
8. Wang, P., Zhou, W., Zhao, Z., & Cavallini, A. (2018, June). The Limitation of Partial Discharge Inception Voltage Tests at Repetitive Impulsive Voltages Using Ultra-High Frequency Antenna and Possible Solutions. In *2018 IEEE Electrical Insulation Conference (EIC)* (pp. 192–195). <https://doi.org/10.1109/EIC.2018.8481044>.
9. Moghadam, D. E., Speck, J., Grossmann, S., & Stahl, J. (2018). Parameters affecting the turn insulation lifetime and durability. *IEEE Transactions on Dielectrics and Electrical Insulation*, 25(2), 516–523. <https://doi.org/10.1109/TDEI.2017.006905>.
10. Hammarström, T. Å. (2018). Partial discharge characteristics within motor insulation exposed to multi-level PWM waveforms. *IEEE Transactions on Dielectrics and Electrical Insulation*, 25(2), 559–567. <https://doi.org/10.1109/TDEI.2017.006994>.
11. Brandt, M., Gutten, M., Koltunowicz, & T., Zukowski, P. (2018). Analysis of winding fault in electric machines by frequency method. *2018 ELEKTRO*. 1–4. <https://doi.org/10.1109/ELEKTRO.2018.8398298>.
12. Yousof, M., Alawady, A., Al-Ameri, S., Azis, N., & Illias, H. (2021, July). FRA indicator limit for faulty winding assessment in rotating machine. In *2021 IEEE International Conference on the Properties and Applications of Dielectric Materials (ICPADM)*. 346–349. <https://doi.org/10.1109/ICPADM49635.2021.9493862>.
13. Al-Ameri, S. M., Alawady, A. A., Yousof, M. F. M., Kamarudin, M. S., Salem, A. A., Abu-Siada, A., & Mosaad, M. I. (2022). Application of frequency response analysis method to detect short-circuit faults in three-phase induction motors. *Applied Sciences*, 12(4), 2046. <https://doi.org/10.3390/app12042046>.
14. Abu-Siada, A., Mosaad, M. I., Kim, D., & El-Naggar, M. F. (2019). Estimating power transformer high frequency model parameters using frequency response analysis. *IEEE Transactions on Power Delivery*, 35(3), 1267–1277. <https://doi.org/10.1109/TPWRD.2019.2938020>.
15. Yousof, M. F. M., Al-Ameri, S., Ahmad, H., Illias, H. A., & Arshad, S. N. M. (2020). A new approach for estimating insulation condition of field transformers using FRA. *Advances in Electrical and Computer Engineering*, 20(1), 35–42. <https://doi.org/10.4316/AECE.2020.01005>.
16. Uhrig, S., Öttl, F., Augeneder, N., & Hinterholzer, R. (2020). Reliable diagnostics on rotating machines using FRA. In *Proceedings of the 21st International Symposium on High Voltage Engineering*. 1. 738–751. [https://doi.org/10.1007/978-3-030-31676-1\\_70](https://doi.org/10.1007/978-3-030-31676-1_70).
17. Fan, F., Zhao, Z., Tu, P., Jie, H., & See, K. Y. (2021, September). Impact of motor stator winding faults on common-mode current. In *2021 Asia-Pacific International Symposium on Electromagnetic Compatibility (APEMC)*. 1–4. <https://doi.org/10.1109/APEMC49932.2021.9597053>.
18. Sant'Ana, W. C., Lambert-Torres, G., Bonaldi, E. L., Gama, B. R., Zacarias, T. G., Areias, I. A. D. S., ... & Steiner, F. M. (2021). Online frequency response analysis of electric machinery through an active coupling system based on power electronics. *Sensors*, 21(23), 8057. <https://doi.org/10.3390/s21238057>.
19. Grubic, S., Aller, J. M., Lu, B., & Habetler, T. G. (2008). A survey on testing and monitoring methods for stator insulation systems of low-voltage induction machines focusing on turn insulation problems. *IEEE Transactions on Industrial Electronics*, 55(12), 4127–4136. <https://doi.org/10.1109/TIE.2008.2004665>.
20. Chumak, V. V., Stulishenko, A. S., Tsyvinskyi, S. S., & Ihnatiev, V. O. (2021). Diahnostyka izoliatsii elektrychnykh mashyn z vykorystanniam komutatsiinykh protsesiv. [Diagnostics of insulation of electric machines using switching processes]. *Enerhetyka: ekonomika, tekhnolohii, ekolohiia: naukovyi zhurnal - Energy: economy, technology, ecology: scientific journal*, 3. <https://ela.kpi.ua/server/api/core/bitstreams/fbd98a31-675b-492e-9a43-c446d4b090f7/content>. [in Ukrainian].
21. Elspass L., Schlegel S., & Bernklau H. (2022). Comparison of methods for detecting thermomechanical aging of the insulation system of rotating high-voltage machines. In *Proceedings of the Nordic Insulation Symposium*. 27. <https://doi.org/10.5324/nordis.v27i1.4570>.
22. Rusu-Zagar, C., Notingher, P. V., & Stancu, C. (2014). Ageing and degradation of electrical machines insulation. *J. Int. Sci. Publ. Mater. Methods Technol*, 8, 526–546. <http://surl.li/tcaact>.

**Юрій Дубравін<sup>1</sup>, Ярослав Шостак<sup>2</sup>, Vitaly Bakhonya<sup>3</sup>, Viktor Tkachenko<sup>4</sup>**

<sup>1</sup>Доцент, кафедра електромеханіки та рухомого складу залізниць, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна. ORCID: <https://orcid.org/0000-0001-9006-5198>

<sup>2</sup>Аспірант, кафедра електромеханіки та рухомого складу залізниць, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна. ORCID: <https://orcid.org/0009-0006-2886-3264>.

<sup>3</sup>Аспірант, кафедра електромеханіки та рухомого складу залізниць, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна. ORCID: <https://orcid.org/0009-0007-5753-2138>.

<sup>4</sup>Професор, кафедра електромеханіки та рухомого складу залізниць, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна. ORCID: <http://orcid.org/0000-0002-5513-2436>

## **Обґрунтування вибору методів діагностики стану ізоляції електричних машин електрорухомого складу залізниць**

*Об'єктом дослідження є процеси моніторингу технічного стану електричної ізоляції тягових електричних машин з метою визначення необхідності їх технічного обслуговування або ремонту. Діагностика електричних машин є важливим аспектом підтримки роботи електроприводів. Відмова обмоток є однією з основних причин виходу з ладу електродвигунів. Тому задача розробки оперативних методів діагностики ізоляції обмоток тягових електродвигунів є актуальною. Виконано дослідження негативного впливу умов експлуатації на технічний стан електричної ізоляції двигунів. Проведено аналіз існуючих методів діагностики ізоляційних систем електричних машин. Особливу увагу приділено вибору прогнозуючих параметрів стану ізоляції. Розроблена математична модель для дослідження частотних характеристик ізоляційної системи статора тягового електродвигуна моделі AD914. Отримано уточнені залежності впливу змін параметрів ізоляції обмотки статора двигуна на його частотні характеристики. Зроблено висновок, що метод моніторингу стану ізоляції обмоток електродвигунів на основі оцінки електричного опору відносно осердя статорів та амплітудно-частотних характеристик є найбільш ефективним. Сферою практичного застосування отриманих результатів є система моніторингу стану електричної ізоляції тягових електричних машин для визначення графіку їх технічного обслуговування і ремонту. Проведені дослідження є науковим обґрунтуванням вибору методів та приладів діагностики стану ізоляції електричних двигунів тягового рухомого складу залізниці.*

**Ключові слова:** діагностування, математична модель, електрична ізоляція, ушкодження, амплітудно-частотна характеристика