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DESIGN OF A MULTILINK SYSTEM FOR CALCULATING HIGH-FREQUENCY PROCESSES IN ELECTRIC MACHINES WITH MESH WINDINGS

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This study considers the design of a multi-link high-frequency circuit for calculating defective and defect-free insulation of mesh windings in order to increase the operational reliability of general-purpose electric machines.

The object of research is mesh windings of electric machines.

The problem to be solved: increasing the operational reliability of electric machines with general-purpose mesh windings by analyzing and modeling defects.

The research results make it possible to model defects for the analysis of the state of insulation of electric machines with mesh windings. Special attention in the research was paid to induction motors with a worn-out resource, in particular, 4A80A4 UZ engine. The analysis includes phase-to-body capacitance, winding inductance, eddy current impedance, and winding impedance.

Under the WN mode, a decrease in the impedance of the winding section from 3 % to the short-circuit mode was simulated; accordingly, the resonance frequencies for each case of 3 % were determined – 73990 Hz, short-circuit – 74450 Hz, as well as the corresponding input impedances 8938.7 and 8082.5. The corresponding voltage resonances and current resonances were also determined. Appropriate results were also given for the WG scheme.

The results reported here relate to the design of the scheme and the research on the defects of the mesh winding. This contributes to the analysis of the state of insulation of mesh windings. The numerical data (resonant frequencies and input impedances) allow a better understanding of the behavior of windings in different states and degrees of defects.

Given the research findings, it is possible to better identify and analyze potential defects in mesh windings, which in turn contributes to increasing the reliability of electric machines.

The results of this study could be used in the field of diagnosis, service, and maintenance of electric machines with mesh windings

Keywords: mesh windings, induction motors, defective insulation, frequency characteristics, high-frequency circuit

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1. Introduction

The task of assessing the condition of the insulating structure of general-purpose electric machines, primarily the turn insulation of mesh windings made of enameled wire, has remained unsolved, despite a large number of studies by various authors, up to this day.

Firstly, it is difficult to obtain reliable results of detecting local defects in the insulation of multi-turn coils (1 and several closed turns or several turns shorted to a transient impedance, which is equivalent to an undevelopeSd local defect).

Secondly, this is an objective defectoscopy of the general condition of the insulation due to complex processes of aging, destruction, as well as the influence of atmospheric factors in machines that do not have previous diagnostic data. That is, it is difficult to compare the results of diagnostics of the machine before operational influences with the current state of the insulation.

Given the complexity of assessing the state of the insulating structure of general-purpose electric machines, especially with mesh windings, the relevance of research into this area is unquestionable. Despite numerous studies, the problem of obtaining reliable results of detection of local insulation defects and objective defectoscopy of the general state of insulation is unsolved. It becomes even more difficult in the context of complex processes of aging, destruction, exposure to atmospheric factors, as well as the lack of previous diagnostic data. Therefore, further research and improvement of diagnostic procedures are critically important for this field.

2. Literature review and problem statement

In [1], interturn short circuits in the stator winding of a generator with permanent magnets are investigated. The authors of the paper propose a method of detecting inter-turn short-circuits for machines with permanent magnets based on the residual current. At the initial stage, the defect analysis was tested on a simplified mathematical model of the machine, and a numerical mathematical model using the finite element method was built to assess the nature of the intact winding insulation. The difference between the measured currents and those calculated in the model is a diagnostic feature that indicates a malfunction. To improve the quality of defect detection, it is suggested to use a controller-filter of the defective winding signal. The method shows good results in detecting insulation defects during transient processes. However, the presence of DC components in the residual current of the reverse sequence can be mistaken for a defect in the insulation of the mesh winding.

Short-circuiting of turns in the stator winding of an electric machine is one of the most serious malfunctions in electric machines. Asymmetry caused by inter-turn short circuits is widely used as a diagnostic method to detect such a fault [2]. However, similar features also occur in cases of less serious defects, such as poor contact, which can lead to incorrect identification of the fault. In the work, the authors propose a method of detecting inter-turn short circuits with the possibility of differentiation from false estimates. According to this method, high-frequency voltage signals of a rectangular shape are used, followed by differentiation of the high-frequency impedance under fault conditions. The proposed method does not depend on operating conditions and is insensitive to transient processes and performs well in diagnosing machines with permanent magnets. However, the use of the proposed method when assessing the state of insulation of asynchronous machines does not provide adequate accuracy due to the influence of the magnetic field of the rotor winding.

Paper [3] deals with the detection of an inter-turn short circuit in the stator mesh windings of asynchronous machines with a short-circuited rotor. The basic principle is to perform harmonic analysis of electrical signals, namely stator phase current, external magnetic flux, and electromagnetic torque at different levels of mechanical load. This is done in order to develop an effective approach to detect this kind of defects in asynchronous machines. The proposed approach is based on the analysis of several factors. The first factor includes $3k1fs$ rank harmonics associated with saturation, where $k1$ is an odd number. The second factor concerns harmonics of rank $((6k2 \pm 1)fs$ associated with the magnetomotive force, with $k2 = 1, 2, \ldots$. These factors are analyzed in the context of the stator phase current. Harmonics at the $2k2fs$ level in the electromagnetic torque are also taken into account.

The amplitudes of these harmonics in good condition are compared with 3 % power supply unbalance, 16.6 % (40 turns), and 33 % (80 turns) short-circuit levels between turns in the frequency range from 0 Hz to 2500 Hz at various mechanical load levels. The study was performed on the basis of a short-circuited induction motor with a capacity of 2.2 kW using the finite element method. This method provides an accurate and inexpensive means of evaluating the performance of an induction machine in the presence and absence of damage. The results demonstrate that the stray flux is the most sensitive feature of inter-turn shorting of the stator winding and it is robust to the imbalance of the power supply compared to both the stator current and the electromagnetic torque. However, the work lacks information about the accuracy of this method and its adequacy for more powerful asynchronous machines with a short-circuited rotor.

A new method of modeling defective and defect-free asynchronous machines with a phase rotor with an interturn circuit using a single set of equations is presented in [4]. The model is given for a machine with an arbitrary number of poles, rotor, and stator. To simulate the behavior of the machine under dynamic regimes, a single set of equations is solved, including both electrical and magnetic parts. Therefore, a modified magnetic equivalent circuit with nonlinear elements is used for modeling, and a numerical method is used to solve the nonlinear equations. The proposed modified method has a simple calculation procedure compared to traditional methods. Solving the electric and magnetic equations using one system of equations is the main advantage of the presented method, which is proposed for a machine with a phase rotor. In addition, to increase accuracy, the model also takes into account the phenomenon of saturation. Because of the saturation effect, there are some nonlinear algebraic magnetic equations that must be solved simultaneously with the differential equations. The finite element method is used to check the effectiveness of the proposed modeling method, although the main criterion for checking the adequacy of the developed model is the experiment.

A mathematical model of a three-phase asynchronous machine, suitable for modeling the behavior of machines under fault conditions, is described in [5]. This work presents a new practical and more accurate model for induction motors after the appearance of inter-turn short circuits. The proposed model is based on the theory of a coupled magnetic circuit, capable of taking into account any conditions of electrical asymmetry. To check the accuracy and efficiency of the model, the simulation results of an asynchronous machine with inter-turn shorting are given. Despite its simplicity, the proposed model provides certain signals for diagnostic purposes. The experimental study reported at the end of the paper shows that the proposed model predicts the behavior of an asynchronous machine with sufficient accuracy.

In [6], a new reliable algorithm for controlling inter-turn circuits for a seven-phase asynchronous machine with a single-phase short circuit is considered. The theoretical foundations of the reconstruction of voltage vectors without the use of a reference current are considered, providing generality for various principles of fault tolerance. A sector division method is proposed based on eight sectors, and five specific non-zero voltage vectors and two zero voltage vectors in each sector. A symmetrical modulation module is also used, which minimizes modifications after a fault occurs. Experimental results demonstrate the effectiveness of the proposed fault-tolerant approach both under stationary and transient modes. The use of multi-phase asynchronous machines can introduce an error when diagnosing inter-turn circuits, especially under asymmetric modes.

The structure of an online monitoring system for the detection of inter-turn faults, combined with many extraction/selection functions and a multi-classifier, capable of detecting defects in asynchronous machines is proposed in [7]. Using signals collected from machines, multiple feature extraction/selection is explored to find defects and different types of classification are used to increase the variety of models based on one. With the increase in the variety of basic signals, it is expected that fault detection accuracy will be improved, and reliability can be guaranteed. The framework of the system has been implemented and verified using real data collected from the developed test bench, with experimental results showing the effectiveness of the framework in detecting inter-turn faults in induction motors. Since this system is based on the analysis of currents, and not the frequency characteristics of the windings, errors are possible when determining defects associated with the presence of parasitic impedances or asymmetry.

The scheme for detecting insulation defects in real time of the stator winding in asynchronous machines is considered in [8]. The non-sinusoidal input voltage and the short circuit cause harmonics in the motor stator current and these combined harmonic components make diagnosis based on spectrum analysis difficult in inverter-fed motors. The purpose of the analysis is to determine the influence of the fundamental frequency and switching frequency of the inverter on the early detection and classification of inter-turn short circuit. A discrete wavelet transform analysis is performed for the stator current using a Dobechy wavelet. The norm of the statistical parameter L_2 is calculated for detailed and approximate coefficients at different levels of decomposition to obtain the most accurate fault characterization. The proposed method does not depend on the switching and fundamental frequency, modulation index and mechanical load. The proposed method enables real-time detection even with an infinitesimally small damage current of 350 mA. The adequacy of the proposed algorithm is confirmed by simulation and verified by hardware with an induction motor drive. The disadvantage of such a system is rather complex and expensive diagnostic equipment, which requires highly qualified service personnel.

Work [9] reports the stray current method for condition monitoring and detection of malfunctions of asynchronous machines, such as inter-turn short circuits of the stator winding. A large magnetostrictive transducer is attached to a fiber Bragg grating to form an FBG-T composite sensor that uses the machine's stray current to sense the machine's internal state. Three states of the machine were studied: working condition, rotor defect, and inter-turn short circuit. A triaxial magnetic flux meter with automatic data logging was used to obtain magnetic flux measurements, and the results obtained with LabView were analyzed in MATLAB. The results of the experiment showed that the FBG-T sensor accurately distinguishes each of the three states of the machine using a different order of magnitude of damage. Despite the high productivity of the method, this approach may have an error when analyzing multi-turn two-layer mesh windings.

In [10], the authors presented a new technique of using an optical fiber to monitor the state of asynchronous machines in the process of detecting an inter-turn short circuit. Optical fiber is immune to magnetic flux. The FBG-T composite transducer is formed by attaching the Terfenol-D magnetostrictive transducer to the fiber Bragg grating. This sensor is used to determine the stray current of machines. The stray current of the machines serves as a signal to determine the state of the internal winding of the machine. Experimental and calculated data agree with each other by that the FBG-T sensor accurately and reliably detects turn-to-turn faults. The Bragg shifts observed during interturn short circuits are almost 10 times greater than when the machine is in a defect-free condition. This research is promising in vehicles, but its effectiveness for use in industrial systems requires additional research.

The presence of an inter-turn short circuit in the mesh multi-flower winding of the stator of an induction motor is one of the most common electrical defects that affects the reliability of industrial equipment. The main limiting factor in the use of the considered approaches for detecting inter-turn short-circuits is the generalization and reliability of diagnostics. There is still no single methodology that provides a comprehensive solution for finding defects in these machines. The availability of different methods for detecting machine defects makes it possible to combine two or more methods in such a way as to provide a more comprehensive solution for monitoring the condition of the machine. Especially considering that these machines will play a significant role in the human transition to a more automated environment where many more electric machines will be needed. The reliability of these machines is critical to minimizing downtime, costs, and the use of human resources. Based on this, it is necessary to evaluate the detection of local defects in the insulation of multi-turn coils and defectoscopy of the general state of the insulation, which is affected by complex processes of aging, destruction, as well as the influence of atmospheric factors.

The issue of reliability of general-purpose electric machines with mesh windings is a serious challenge. It implies the need to improve existing scientifically based methods of winding insulation diagnostics.

In addition, the development of new, more effective methods is needed. These methods should make it possible to detect the actual state of the least reliable links of the insulating structure.

3. The aim and objectives of the study

The purpose of our research is to design a multi-link high-frequency circuit for calculating defective and defect-free insulation of mesh windings to increase the operational reliability of general-purpose electric machines. This will make it possible to model defects for the analysis of the state of insulation of electric machines with mesh windings.

To achieve the set goal, the following tasks must be solved:

– to substantiate the theoretical prerequisites of electrophysical electro frequency processes in the windings of electric machines with mesh windings;

– to propose and justify an equivalent high-frequency substitution scheme for calculating and analyzing high-frequency processes;

– to carry out modeling of a defect-free mesh winding and in the presence of inter-turn short-circuits.

4. The study materials and methods

Research object: insulation of stator windings of induction motors with a worn-out resource, methods and means of its diagnosis.

Data of the engine under study:

– 4A80A4 UZ;
– power (P) – 1.1 kW;
– sliding s – 6.7 %;
– efficiency – 75 %;
– cosφ=0.81;
– $M_{\max}=2.2$;
– $M_{starting}=2$;
– $M_{\min}=1.6$;
– $I_{starting}=5$;
– capacitance between phase and body (K) – 0.25 nF;
– winding inductance (L') – 31 Mh;
– impedance created by eddy currents (r) – 17.49 kOhm;
– winding impedance – 7.8 Ohm.

The main hypothesis of the research: regularities of the connection between the frequency characteristics and the presence of integral and local insulation defects of induction motors with lumped windings, namely:

1. The frequency characteristics of the insulation of the stator windings of induction motors can reflect the state of the insulation.

2. There is a direct or indirect relationship between the frequency characteristics and insulation defects of induction motors with mesh windings.

3. Local and integral insulation defects have a significant effect on frequency characteristics.

Assumptions adopted in the study:

1. In the proposed chain substitution scheme, the number of links is limited to six units, which to some extent reduces the accuracy of calculations but does not affect the adequacy of the obtained results.

2. Eddy current losses and hysteresis in the magnetic core are not taken into account in the mathematical model.

3. The discreteness of the internal and external boring of the stator and rotor is not taken into account.

4. The longitudinal inter-turn and inter-coil capacitance of the winding is not taken into account Simplifications adopted in the study:

4. 1. The study considers only certain types of induction motors with mesh windings having a worn-out resource in order to focus on a specific class of problems.

4. 2. The structure and insulation materials of induction motors are uniform and standard for this study.

4. 3. The focus is on the known and common types of insulation defects that affect the stability of the parameters of induction motors with mesh windings.

5. Research results of a multi-link system of calculations of high-speed processes of electric machines with mesh windings

5. 1. Theoretical prerequisites of electrophysical electro frequency processes in the windings of electric machines with mesh windings

Studying the operation of an electric machine and reviewing switching, wave and pulse processes requires a mathematical description of the winding. In general, the real winding is a complex system. The heterogeneity of the system is obvious since the turns of even one coil have different parameters depending on the position in the groove, not to mention that within one turn, the specific parameters of the active and frontal parts differ. The transition from one coil to another is obvious, that is, the system is discrete and homogeneous. Therefore, the widely used representation of the winding in the form of a long homogeneous line with distributed parameters will usually give significant errors when examining the processes inside the winding. A similar model with averaged parameters is used to estimate input and wave impedances. However, for the calculation of modes, the use of this model complicates calculations without approaching the physical essence [11].

Windings of electric machines represent systems of elements with frequency-dependent parameters. At sufficiently high frequencies, the magnetic fluxes of the windings are expressed in dissipation fluxes, closing mainly by non-magnetic means. Therefore, the parameters of the windings at high frequencies practically do not depend on voltage. Considering the experimental frequency dependences $Z_{input}(\omega)$ taken for small engines and similar characteristics for large machines, we can conclude that they are qualitatively similar but there are large differences in the design and dimensions of the windings.

In these dependences, the magnitude and ratio of resonant frequencies under the no-load operation and short circuit modes are characteristic. Let's consider these relations in different models.

When the winding is represented by a long uniform line, the input impedance is determined by equation (1):

$$Z_{input} = \frac{Z_2 Ch\gamma l + Z_v Sh\gamma l}{Z_2 Sh\gamma l + Z_v Ch\gamma l}. \quad (1)$$

For the limit modes – idling ($Z_2=\infty$) and short circuit ($Z_2=0$), the input impedances are equal to [2]:

$$Z_0 = Z_v \frac{Ch\gamma l}{Sh\gamma l}, \text{ and } Z_{s.\,c.} = Z_v \frac{Sh\gamma l}{Ch\gamma l}. \quad (2)$$

For the first resonant frequencies, neglecting the losses in the system, we use the formula:

$$\gamma l = \sqrt{Z'Y'} \cong j\omega I\sqrt{L'C'} = j\omega\sqrt{LC}, \quad (3)$$

where Z' and Y' are resistivity and conductivity [4].

Accordingly:

$$Z_0 = -jZl\mathrm{ctg}\left(\omega\sqrt{LC}\right) \text{ and } Z_{s.\,c.} = jZ_v\mathrm{tg}\left(\omega\sqrt{LC}\right). \quad (4)$$

The first resonant frequencies of the specific input impedances of the linear model are 1:2.

The frequencies of the first harmonics /$k=0$/ according to the voltage resonance conditions are, respectively, (5):

$$\omega_0 = \frac{\pi}{2\sqrt{LC}}, \text{ and } \omega_{s.\,c.} = \frac{\pi}{\sqrt{LC}}. \quad (5)$$

For the chain model, the free transition functions at the input of the chain from m n-like quadrupoles (6), (7):

$$A_0(t) = \frac{1}{m}\sqrt{\frac{C'}{L'}}\sum_{k=1}^{m}\frac{\cos^2\frac{a_{s.\,c.}}{2}}{\sin^2\frac{a_{s.\,c.}}{2}}\sin\omega_{s.\,c.}t, \quad (6)$$

where $a_{s.\,c.} = \frac{2K-\pi}{2m}$, $\omega_{s.\,c.} = \frac{2}{\sqrt{L'C'}}\sin\frac{a_{s.\,c.}}{2}$,

$$A_{s.\,c.}(t) = \frac{1}{m}\sqrt{\frac{C'}{L'}}\sum_{k=1}^{m}\frac{\cos^2\frac{a_{s.\,c.}}{2}}{\sin^2\frac{a_{s.\,c.}}{2}}\sin\omega_{s.\,c.}t, \quad (7)$$

$$a_{s.\,c.} = \frac{K\pi}{2m}, \omega_{s.\,c.} = \frac{2}{\sqrt{L'C'}}\sin\frac{a_{s.\,c.}}{2},$$

when $K=1$ and $m\to 0$, the coefficients $a_{s.c.}\to 0$, but the inductance $L'=L/m$ and capacity $C'=C/m$ of each four-pole also tend to 0 and, accordingly, $\omega_{1x} = \pi/2\sqrt{LC}$ and $\omega_x = \pi/2\sqrt{LC}$, that is, the resulting expressions are similar to the linear model.

When the number of links is reduced, the corresponding frequencies will change [12].

5. 2. High-frequency replacement circuit for calculations and analysis of processes in mesh windings

The winding of an electric machine can be represented in the form of a multi-link substitution scheme taking into account the properties of its winding (number of turns, number of sections). Fig. 1 shows a separate link of a multi-link substitution scheme.

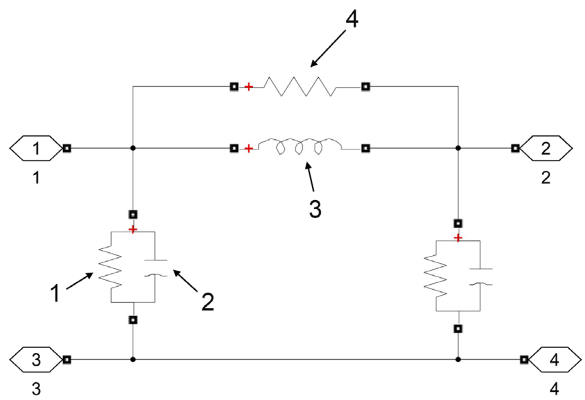

Fig. 1. Equivalent diagram of the motor winding section: 1 – transverse electrical impedance; 2 – transverse capacitance; 3 – inductance; 4 – longitudinal impedance

Varying these parameters allows us to draw conclusions about a disruption of the insulation system inside the winding section. This can be a shorting of the turns, which leads to a decrease in the impedance of the section.

Based on the data specified in chapter 4, an equivalent high-frequency circuit of the mesh winding of an electric machine was built in the Matlab Simulink (USA) environment.

Designation:

– transverse electrical impedance is the impedance of the winding insulation relative to the body;

– transverse capacitance is the insulation capacitance relative to the case;

– inductance is the total inductance of the winding;

– longitudinal impedance is the longitudinal active impedance of the winding;

– WG – winding-ground connection (body);

– WN – winding-neutral connection.

The study of defects in this work is carried out at a constant temperature of the environment and the motor winding, respectively. This is due to the fact that this method provides a test mode for diagnosing the winding, during scheduled repairs or maintenance.

This method is not used when the engine is operating when the temperature varies within certain limits. This can also be attributed to one of the advantages of the proposed method.

Fig. 2 shows the equivalent circuit for replacing the motor winding.

When affected by fast-moving processes, it is important to take into account such indicators that are not valid at the operating frequency, namely, the inductance of the winding link, which in this case is a section, capacitance per case, impedance per case [13].

5. 3. Results of simulation of a defect-free mesh winding and in the presence of inter-turn short-circuits

The frequency characteristic according to the WG scheme (winding relative to the motor body) for the non-defective state of the motor winding is shown in Fig. 3.

The frequency characteristic according to the WN scheme (winding relative to the middle point of the motor winding) for the non-defective state of the motor winding is shown in Fig. 4.

The frequency characteristic according to the WG scheme, which characterizes the impedance of one section reduced by 3 %, is shown in Fig. 5.

The frequency response according to the scheme WN, relative to the impedance of one section, which is reduced by 3 %, is shown in Fig. 6.

The frequency response according to the WG scheme, corresponding to the impedance of one section, reduced by 5 %, is shown in Fig. 7.

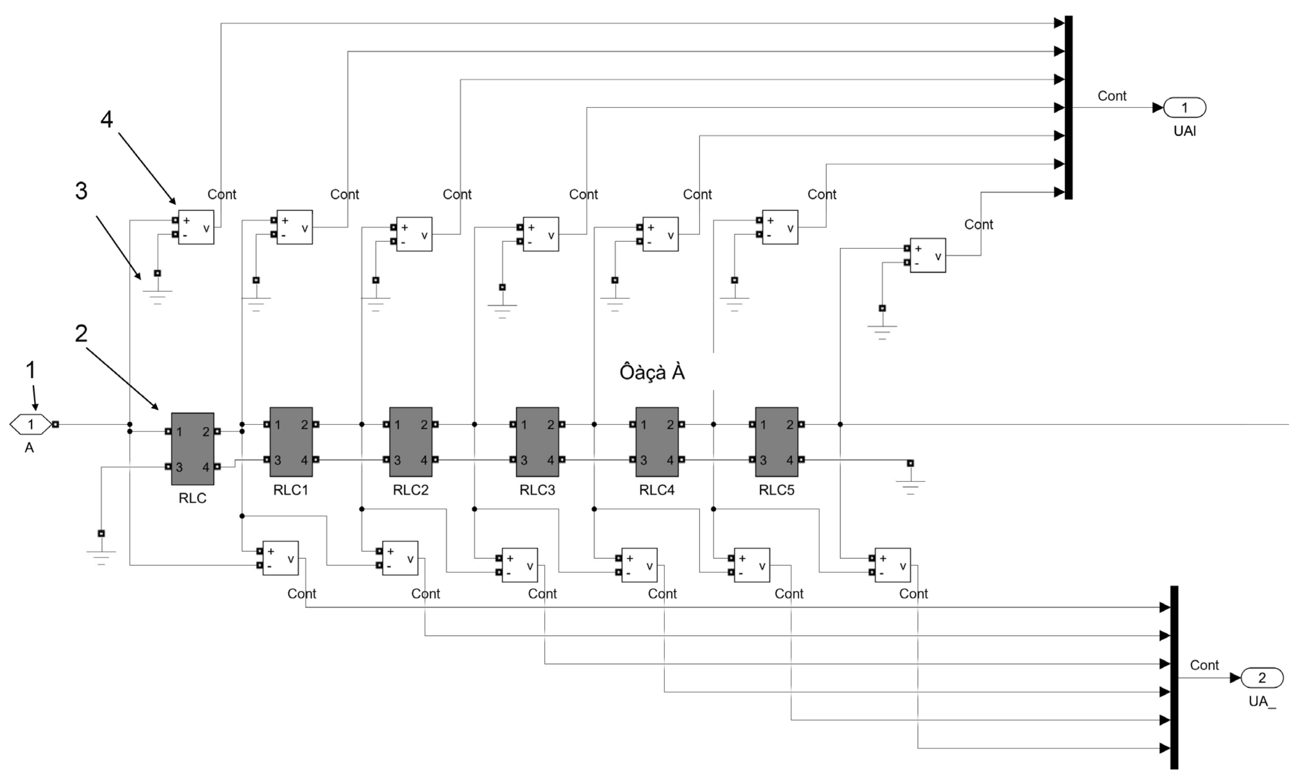

Fig. 2. Equivalent motor winding replacement circuit: 1 – replacement circuit terminals; 2 – motor winding section; 3 – grounding; 4 – voltmeter; 5 – output to the neutral

The frequency response according to the scheme WN, which corresponds to the impedance of one section reduced by 5 %, is shown in Fig. 8.

The frequency response according to the WG scheme, which corresponds to the impedance of one section of the winding reduced by 10 %, is shown in Fig. 9.

The frequency response according to the scheme WN, corresponding to the impedance of one section of the winding reduced by 10 % is shown in Fig. 10.

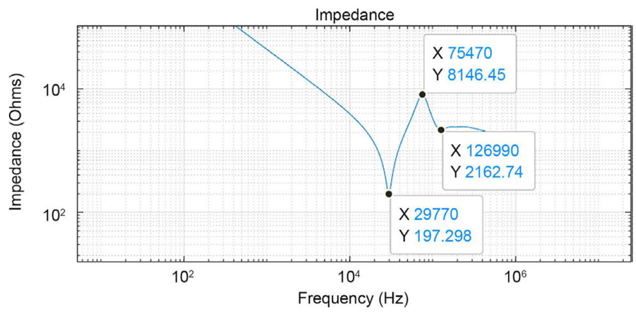

Fig. 3. Frequency response according to the WG scheme without defect

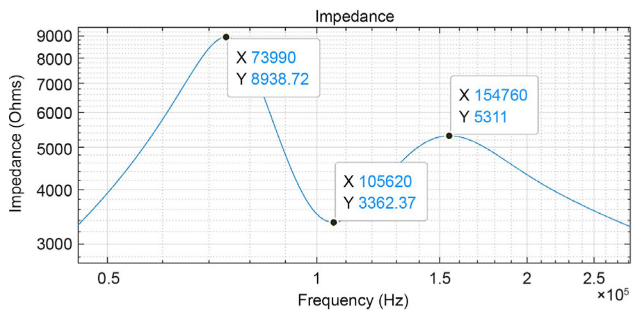

Fig. 4. Frequency response according to the WN scheme without defect

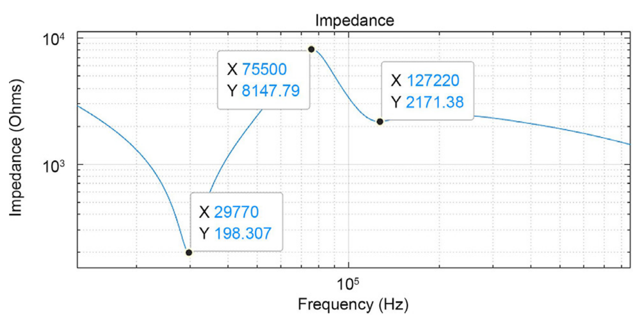

Fig. 5. Frequency response according to the WG scheme: the impedance of one section is reduced by 3 %

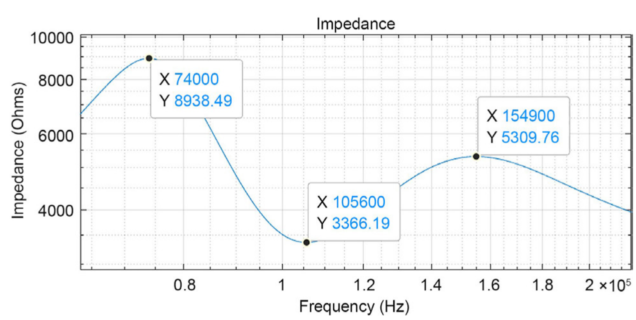

Fig. 6. Frequency response according to the WN scheme: the impedance of one section is reduced by 3 %

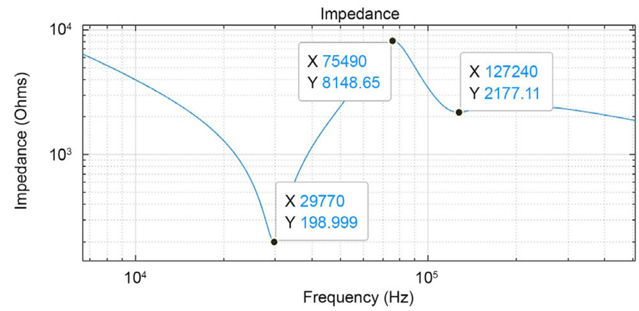

Fig. 7. Frequency response according to the WG circuit: the impedance of one section is reduced by 5 %

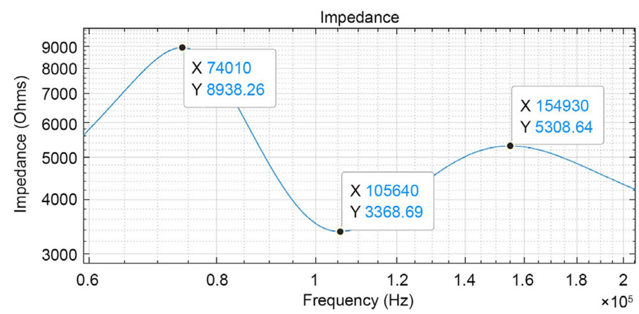

Fig. 8. Frequency response according to the WN scheme: the impedance of one section is reduced by 5 %

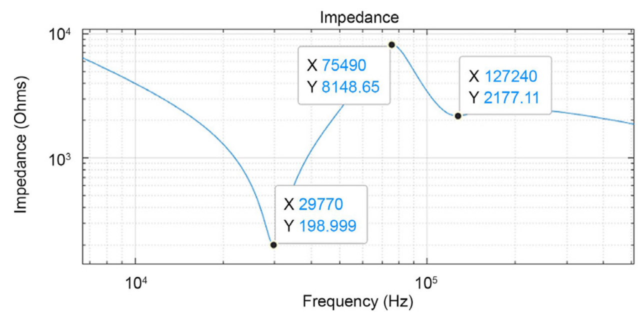

Fig. 9. Frequency response according to the WG circuit: the impedance of one section is reduced by 10 %

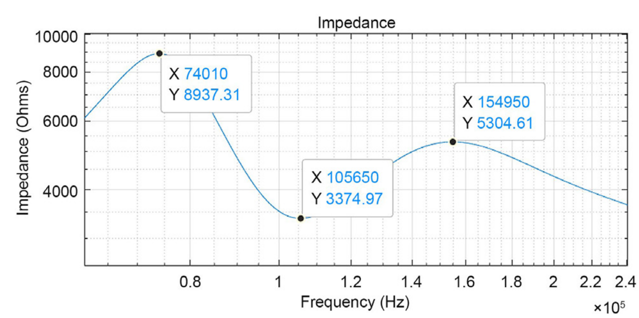

Fig. 10. Frequency response according to the WN scheme: the impedance of one section is reduced by 10 %

The frequency response according to the WG scheme, which corresponds to the impedance of one section of the winding reduced by 20 %, is shown in Fig. 11.

The frequency response according to the scheme WN, which corresponds to the impedance of one section of the winding reduced by 20 %, is shown in Fig. 12.

The frequency response according to the WG scheme, which corresponds to the impedance of one section of the winding reduced by 99 %, is shown in Fig. 13.

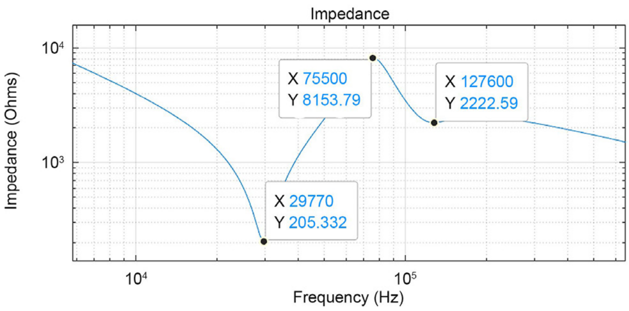

Fig. 11. Frequency response according to the WG scheme: the impedance of one section is reduced by 20 %

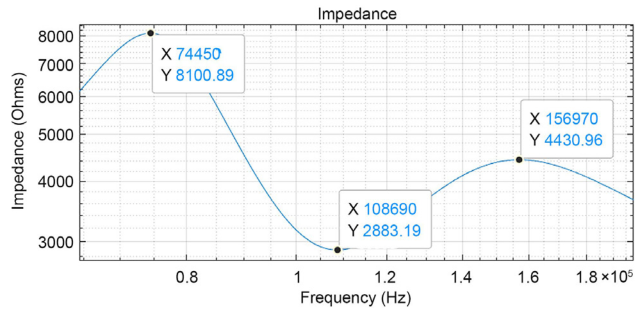

Fig. 14. Frequency response according to the WN scheme: the impedance of one section is reduced by 99 %

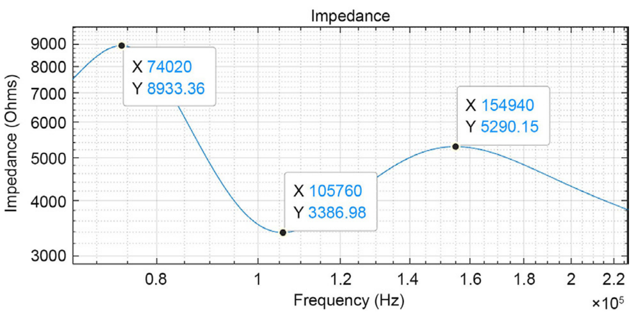

Fig. 12. Frequency response according to the WN scheme: the impedance of one section is reduced by 20 %

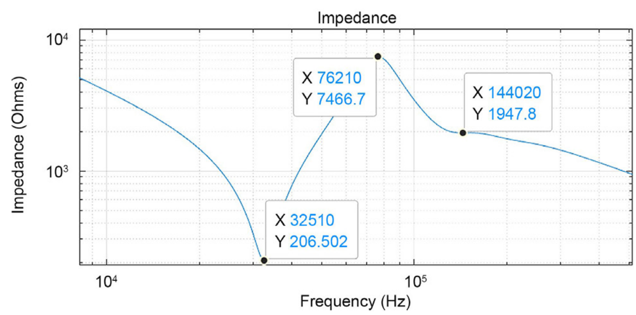

Fig. 15. Frequency response according to the scheme WG short circuit section

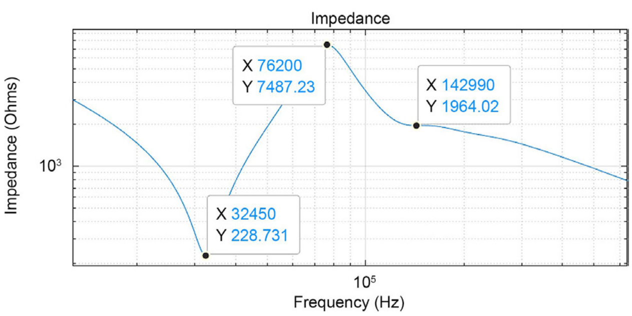

Fig. 13. Frequency response according to the WG circuit: the impedance of one section is reduced by 99 %

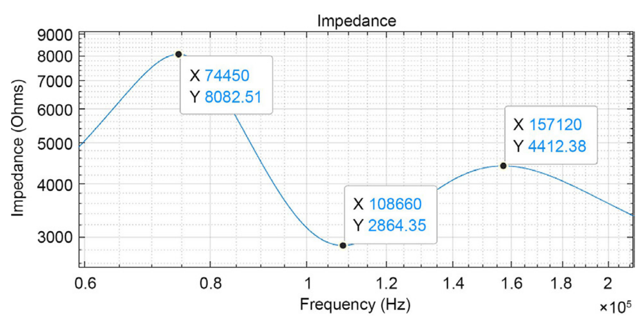

Fig. 16. Frequency response according to the scheme WN short circuit section

The frequency response according to the scheme WN, which corresponds to the impedance of one section of the winding reduced by 99 % is shown in Fig. 14.

The frequency response according to the WG scheme at a short circuit of the motor stator winding section is shown in Fig. 15.

The frequency response according to the WN scheme at a short circuit of the motor stator winding section is shown in Fig. 16.

The simulation results of the investigated motor with varying degrees of defectiveness of winding insulation according to the WG connection scheme are summarized in Table 1.

The simulation results of the investigated motor with varying degrees of defectiveness of winding insulation according to the WN connection scheme are summarized in Table 2.

The dta given in Tables 1, 2 are used to determine the degree of defectiveness of the winding insulation during its operation.

Table 1

Simulation results with varying degrees of defective windings insulation according to the WG connection scheme

WG		0 %	3 %	5 %	10 %	20 %	99 %	S.C.
1 resonance (voltages)	*f*, Hz	29770	29770	29770	29770	29770	32450	32510
	Z, Ohm	197.3	198.3	199	200.9	205.3	228.7	206.5
2 resonance (currents)	*f*, Hz	75470	75500	75490	75510	75500	76200	76210
	Z, Ohm	8146.5	8147.8	8148.7	8150.7	8153.8	7487.2	7466.7
3 resonance (voltages)	*f*, Hz	126990	127220	127240	127200	127600	142990	144020
	Z, Ohm	2162.7	2171.4	2177.1	2191.9	2222.6	1964	1947.8

Table 2

Simulation results of motor with varying degrees of defectiveness of windings insulation according to the WN connection scheme

WN		0 %	3 %	5 %	10 %	20 %	99 %	S.C.
1 resonance (currents)	*f*, Hz	73990	74000	74010	74010	74020	74450	74450
	Z, Ohm	8938.7	8938.5	8938.3	8937.3	8933.3	8100.9	8082.5
2 resonance (voltages)	*f*, Hz	105620	105600	105640	105650	105760	108690	108660
	Z, Ohm	3362.4	3366.2	3368.7	3375	3387	2883.2	2864.4
3 resonance (currents)	*f*, Hz	154760	154900	154930	154950	154940	156970	157120
	Z, Ohm	5311	5309.76	5308.6	5304.6	5290.2	4431	4412.4

6. Discussion of the multi-link system of calculations of high-frequency processes in electric machines with mesh windings

This paper proposes a unique approach to detecting defects in the windings of an induction motor based on the analysis of resonance frequencies and impedances. In contrast to known works [2, 4], the proposed method is based on the use of high-frequency analysis (and corresponding high-frequency impedances). The method is sensitive to resonance frequencies that change with different degrees of winding insulation defects, which are not taken into account by known methods of diagnosis [5–7]. Due to the use of the proposed approach, it is possible to increase the accuracy and reliability of diagnosing defects in the insulation of mesh windings in comparison with known methods [1, 3, 8, 10].

Compared to existing methods, the proposed approach is more sensitive to minor changes in the insulation condition of the mesh winding. This provides more accurate and timely diagnostics, which in turn contributes to improving the performance and reliability of electric machines.

An equivalent high-frequency circuit of the mesh winding of an electric machine was designed in the Matlab Simulink environment (Fig. 1). The scheme takes into account all the electrical impedances of the winding insulation, which affect the process of diagnosing the state of the insulation: transverse electrical impedance, transverse capacitance, inductance, longitudinal impedance.

On the basis of the high-frequency scheme (Fig. 1), an equivalent scheme for replacing the mesh winding of the motor has been built on which different degrees of insulation damage are simulated.

Voltage resonance and current resonance are specific states on the frequency characteristics of the induction motor winding (Fig. 3, 4). They occur when the winding impedance reaches its maximum or minimum value. This happens due to the coincidence of the operating frequency with one of the resonance frequencies (Fig. 5, 6).

Voltage resonance occurs when the voltage frequency coincides with the resonance frequency (Fig. 7, 8), at which the reactive impedances of the inductive and capacitive elements in the electric circuit compensate each other (X_L=X_C) (Fig. 9, 10). In this state, the impedance of the winding will be minimum, and the current in the winding will reach its maximum value.

Current resonance occurs when the voltage frequency coincides with the resonance frequency at which the total impedance of the winding reaches its maximum value (Fig. 11, 12). In this state, the current in the winding will be minimal.

The analysis of resonance phenomena on the frequency characteristics of the winding of an induction motor helps determine the operating frequency ranges, avoid dangerous conditions, and reveal the degree of defectiveness of the insulation of the windings (Fig. 12–16).

The resonance of voltages and currents are important indicators in the frequency characteristics of the winding of an induction motor, which allow detecting changes in the state of the winding based on the analysis of resonance frequencies and impedances (Fig. 3–16). Corresponding changes in resonant frequencies and impedances are useful for motor condition diagnostics as they reflect varying amounts of winding defects.

Our studies of frequency characteristics for the WG scheme (Table 1) for various sizes of defects in the winding of an induction motor show the following:

1. The values of resonant frequencies and impedances change depending on the size of the defects, which indicates the possibility of detecting changes in the state of the motor winding based on these data.
2. As the size of the defect increases, there is a change in resonant frequencies and impedances for each resonant mode. In particular, with significant defects (99 % and short circuit), there is a significant change in resonant frequencies and impedances compared to smaller defects.
3. Given the different resonant modes, the analysis of their frequency characteristics can help in detecting defects and degradation of the winding.

Based on the given data on voltage resonance and current resonances for the WN circuit (Table 2) for different sizes of defects in the winding of an induction motor, it is possible to make the following conclusions:

1. The values of resonance frequencies and impedances change depending on the size of the defect. This indicates the possibility of detecting changes in the state of the motor winding based on this data.
2. For each resonant mode, there is a change in resonant frequencies and impedances with an increase in the size of the defect. In particular, with significant defects (99 % and short-circuit), there is a significant change in resonant frequencies and impedances compared to smaller defects, but even minor defects can be diagnosed with the help of high-precision equipment.
3. Detection of winding defects: changes in resonant frequencies and impedances may indicate the presence of

defects in the motor winding, such as short circuits, short circuits in multiple turns, or insulation degradation due to aging and moisture.

4. Determining the degree of defect: analysis of changes in resonance frequencies and impedances depending on the size of the defect can help in determining the state of degradation of the motor winding.

Therefore, data on voltage resonance and current resonance can be useful for diagnosing the condition of an induction motor.

The following advantages and features of the proposed solutions can be distinguished:

Integrated approach. The schemes designed in the Matlab Simulink environment take into account all the electrical impedances of the winding insulation, which affect the process of diagnosing the state of the insulation. This includes transverse electrical impedance, transverse capacitance, inductance, longitudinal impedance. Such a holistic approach can improve diagnostic accuracy.

Detailing. The proposed schemes simulate different degrees of insulation damage, which allows for a detailed study of the effect of various defects on the behavior of the machine.

Adaptability. The values of resonant frequencies and impedances change depending on the size of the defects. Such adaptability improves the ability to detect changes in the state of the motor winding.

Specificity. This approach allows detection of various types of defects, including short circuits, multiple turns, or insulation degradation due to aging and moisture.

Precision. Frequency characteristics make it possible to detect even minor defects with the help of high-precision equipment.

Evaluation of the degree of defect. Analysis of changes in resonant frequencies and impedances depending on the size of the defect can help determine the state of degradation of the motor winding.

Therefore, compared to other known methods, the proposed solutions allow more accurate, flexible, and detailed diagnosis of the state of insulation of the winding of an electric machine, as well as detecting various types of defects, including less significant ones, which significantly increases the efficiency of diagnostics.

The greatest difficulties arise when assessing the defects of multi-turn mesh windings, which are difficult to model. Defect modeling using a high-frequency substitution scheme brings this model closer to a real winding with an appropriate number of sections. Each section is our link, which makes it possible to simulate defects in different parts of the winding and assess the degree of its destruction.

There are several potential limitations that may arise in practical application and further research, listed below.

Limitations of the model. All mathematical models have their limitations. Our schemes may not take into account some important aspects of physical reality, which may lead to inaccuracies in their predictions.

Equipment accuracy. The study notes that even minor defects can be diagnosed using high-precision equipment. However, the availability and accuracy of such equipment may be limited.

Interpretation difficulties. Although changes in resonant frequencies and impedances can indicate the presence of defects, there can be challenges associated with correctly interpreting these data, especially in complex or ambiguous situations.

Limitations of the methodology. The study may have limitations related to the use of Matlab Simulink or other technologies and methods used. For example, there may be limitations in modeling different degrees of damage or in the realism of investigating different types of defects.

The disadvantages of the study are the lack of experimental confirmation, the lack of analysis of the influence of external factors; the humidity of the insulation, the change in temperature, and partial discharges are not taken into account.

The development of this study may consist in comparing this theoretical study with a real machine and its characteristics recorded by appropriate equipment and designed devices.

7. Conclusions

1. The theoretical prerequisites of electrophysical electrofrequency processes in the windings of electric machines with mesh windings have been substantiated. When a defect in the mesh winding appears, the resonant frequency changes, which is a reliable identifier of the presence and degree of insulation damage. This makes it possible to obtain dependences of the value and ratio of resonant frequencies under the modes of non-working operation and short circuit.

2. A multi-link high-frequency substitution scheme was built for calculations and analysis of high-frequency processes in mesh windings of electric machines. The scheme for replacing fast-moving processes takes into account indicators that do not appear at the operating frequency, namely, the inductance of the winding section, the capacitance of the winding section relative to the housing, and the impedance of the winding relative to the housing. This makes it possible to obtain a system of diagnostic signs for detecting defects in the inter-turn insulation of mesh windings.

3. As the size of the defect increases, there is a change in resonant frequencies and impedances for each resonant mode. In particular, with significant defects (99 % and short circuit), there is a significant change in resonant frequencies and impedances compared to smaller defects. Changes in resonant frequencies and impedances may indicate defects in the motor winding, such as short circuits, multiple turns, or insulation degradation due to aging and moisture. Analysis of changes in resonant frequencies and impedances depending on the size of the defect can help determine the state of degradation of the motor winding.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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