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DETECTING INSULATION DEFECTS IN ELECTRICAL MACHINES' MULTI-TURN WINDINGS BASED ON ANALYSIS OF TRANSIENT ELECTROMAGNETIC PROCESSES

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This study investigates transient processes occurring in a squirrel-cage induction motor with a stator's multi-turn winding. These processes are used to devise efficient and simple diagnostic methods for assessing the condition of the least reliable element in an electrical machine – the winding insulation. This paper solves the task related to enhancing the operational reliability of electrical machines with multi-turn windings.

The proposed high-frequency model of transient processes in multi-turn windings of electrical machines aims to non-destructively diagnose the insulation. This model enables analysis of high-frequency and impulse phenomena with an equivalent frequency of up to tens of MHz, which may arise during the operation of the machine because of switching and atmospheric overvoltage, as well as when powering electric motors with inverters. Underlying the model is the frequency and time domain analyses under above-mentioned influences using a low-power multi-turn induction motor as an example.

To construct the model, a multi-segment equivalent circuit was used, represented as a series of connected four-poles with inductive-resistive-capacitive parameters corresponding to sections of the winding phase with conditionally uniform concentrated parameters.

The constructed model and the proposed method make it possible to achieve the necessary test overvoltage to detect hidden and undeveloped defects at minimal sparing energy impact, without causing its irreversible destruction. Taking into account the distributed parameters of the winding sections combined with the impulse nature of the excitation ensure non-destructive testing (or non-destructive evaluation) of multi-turn-wound AC machine windings compared to classical testing methods.

The proposed method makes it possible to obtain 2–2.5 times higher longitudinal test gradients with a comparable energetic impact at the level of 0.1 J. The results will contribute to improving the reliability of electrical machine operation in industrial settings by integrating the devised method into the system of planned preventive maintenance of electrical equipment

Keywords: high-frequency model, equivalent circuit, wave processes, diagnostics of winding insulation

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1. Introduction

The task to achieve reasonable reliability of electric machines, in particular general-purpose induction motors, has been and remains an urgent issue. The least reliable link in an electric machine is the insulation of the windings [1]. One of the main and determining factors affecting the service life of the insulation is thermal aging [2]. However, operating experience shows that switching overvoltage exerts a significant impact on the reliability of the windings [3]. Switching overvoltage, when operating an electric machine, occurs during frequent switching and reversing at idle. Industrial statistics and the results from accelerated tests of electric motors for reliability show that switching overvoltage in the presence of a through insulation defect cause an electrical breakdown. It turns into a thermal breakdown with subsequent destruction of a significant part of the winding and a sudden breakdown of the electric machine as a whole [4]. Accordingly, it is possible to use test impulse effects with minimal energy for partial electrical breakdown of insulation at the site of an undeveloped defect without the process evolving into a thermal breakdown, which partially simulates operational switching overvoltage.

Therefore, research on diagnosing the insulation of multi-turn windings in electrical machines based on transient processes remains relevant.

2. Literature review and problem statement

In [5], a hybrid approach to feature selection and classification of partial discharge signals in electrical machine insulation is proposed, which is based on a combination of methods for diagnosing electrical machine insulation. The methodology is implemented by studying four types of insulation defects under laboratory conditions. The effectiveness of the proposed method is evaluated in comparison with other feature selection algorithms. It is shown that the combination of the rms resistance estimation method and the frequency method makes it possible to achieve the highest accuracy. The key advantage of the reported advancement is the high accuracy of the method and its potential suitability for diagnosing other elements of power systems. However, the disadvantage of the study is the lack of results of implementing the method in actual operation, which limits the practical effectiveness of the results.

This very approach to partial discharge identification is considered in [6], in which the authors proposed a method for feature selection based on black-and-white images obtained from phase-resolved sequences of partial discharge pulses. As a processing method, the use of fast transformation in combination with an improved support vector algorithm for the classification of partial discharge sources is proposed. A feature of the study is the consideration of the influence of phase and spatial separation of images, as well as the presence of noise, which makes the proposed method suitable for real-world application conditions. Although the proposed solution demonstrates good resistance to interference, the work does not give the results from practical implementation, which casts doubt on its applicability.

A more detailed study in this area is reported in [1], which considers the influence of the parameters of the electrical insulation system on the reliability of electrical machines, especially in critical applications such as electric vehicles and aviation. The authors show how the dimensions of the enameled copper winding, the material of the slot insulation, the type of impregnating agent, and the use of insulation with high thermal conductivity affect the temperature regime and losses in the winding and magnetic core. The study is based on a specific example for aviation systems. However, the paper does not provide a sufficiently detailed description of the mathematical and experimental modeling taking into account the conditions of real operation, which complicates the adaptation of the described approaches to other types of electrical machines.

A fundamentally different approach is given by the authors of [7] who report an approach to increasing the reliability of low-voltage electrical machines powered by a frequency converter. A feature of these electrical machines is that they have a high specific power. The authors propose using a methodology based on failure physics instead of the traditional engineering approach with the corresponding development of a design concept focused on avoiding partial discharges as the main cause of its failure. This approach makes it possible to ensure a balance between reliability and specific power of electric machines at the design stage. However, the results are based mainly on the analysis of previous studies and are not accompanied by full-scale experimental confirmation, which limits their practical verification.

That research is advanced by work [8], which considers the problem of partial discharges in the insulation of electric machines of aircraft caused by high-frequency voltages of a rectangular shape and reduced atmospheric pressure. For this purpose, a specialized experimental platform was designed using the reduced-frequency ultrahigh-frequency method and the optical method, which make it possible to effectively record partial discharge pulses. The study was conducted on samples of twisted conductors at different pressures (up to 20 kPa) and pulse repetition frequencies (up to 5 kHz). It is shown that with a decrease in air pressure and an increase in pulse frequency, the minimum voltage of partial discharge onset decreases. Analysis of the electric field distribution and relaxation processes in the winding insulation was performed. However, despite the novelty of the approach, the results remain confined to laboratory conditions without further scaling to real electrical machines, which limits the practical application of the results.

A variation of the study on partial discharges is given in [9]. A combined method for detecting partial discharges in the insulation of electric motors based on the mixing method and the photoelectric method using a silicon photomultiplier is considered. This approach is aimed at reducing the impact of electromagnetic interference that occurs when the motor is powered by a rectangular voltage. However, despite the in-depth analysis of physical processes and laboratory confirmation of the results, no comparison with other diagnostic methods is provided and there are no examples of practical application of the results for actual designs of electric motors, which limits the applied value of the study.

In [10], the features of insulation diagnostics associated with the development of electromechanical energy converters with wet windings are considered. The authors provide a general overview of the features of the operation of power supply systems of such motors at increased supply voltage, but at the same time it complicates ensuring the reliability of the insulation operation. The problems of insulation of electric machines, power modules, cable products, etc. are considered. The technical barriers associated with the design of insulating materials and the development of test methods for new operating conditions are summarized. However, the paper lacks an in-depth analysis of specific solutions or examples of adapting insulating systems to conditions of reduced air density and high switching frequency, which limits the applied usefulness of the material for new generation design solutions.

In [11], a review of current research on the influence of temperature, pressure, and humidity on the activity of partial discharges, which is a key factor in the aging and destruction of insulation in electrical machines, is given. The authors conduct an analysis based on individual environmental factors, examining in detail the types of samples, the forms of applied voltage, the mutual influence of environmental parameters, as well as the models used to describe partial discharges. The possibility of using partial discharge measurements to estimate the error is discussed. However, the paper does not analyze the practical suitability of the considered models for the operating conditions of real electrical machines, and no conclusions are drawn regarding the accuracy and reliability of prediction methods based on the revealed patterns.

Work [12] builds on previous research by considering an issue related to ensuring the reliability of general-purpose electrical machines taking into account the requirements of high specific power and compactness. The authors emphasize the need for a balance between reliability and efficiency and propose the application of the theory of "failure physics" at the design stage as a means of overcoming the limitations of the conventional "over-redundancy" method. The paper highlights the main factors of aging of the insulation system of windings, reviews materials, manufacturing processes, loads acting on the insulation, and presents models for predicting the service life. However, the review does not include a comparative analysis of the accuracy or advantages of different models for predicting the service life, which complicates the choice of the optimal approach for specific conditions.

We can conclude that the task of diagnosing the condition of the insulation of multi-turn windings in electrical machines is becoming increasingly relevant due to the growing requirements for increasing the reliability of their operation [13]. The basic method for studying the quality of interturn insulation involves considering partial discharges [14] as a key cause of insulation aging, as well as devising methods for their defect detection under the action of high-frequency voltage of a rectangular shape. And, additionally, the influence of variable environmental parameters – pressure, temperature, humidity – on the occurrence of partial discharges [15].

However, most available studies do not highlight in detail the influence of the type of conductor, winding laying technology, and structural features of the multi-turn sections on the nature and dynamics of evolution of interturn insulation defects. There is a lack of studies that would comprehensively consider the interaction between the impulse load and mechanical stresses in the insulation system. Given this, it is advisable to conduct a comprehensive study on transient electrophysical processes in the insulation systems of multi-turn windings in electrical machines, taking into account the influence of external factors and typical operating modes. Special attention should be paid to devising the methods for high-frequency diagnostics of undeveloped defects, as well as modeling insulation degradation mechanisms to predict its resource under conditions of impulse voltage.

3. The aim and objectives of the study

The purpose of our work is to devise a method for diagnosing the insulation of the multi-turn windings in electric machines based on the analysis of transient electromagnetic processes caused by pulse overvoltage. This will increase the reliability of assessing the technical condition of electric machines' insulation, improve operational reliability, and reduce the costs of emergency repairs and equipment downtime in the energy, industrial, transport industries, etc.

To achieve this aim, the following objectives were accomplished:

– to theoretically substantiate a method for solving the task of building a high-frequency numerical simulation model;

– to determine the high-frequency winding parameters for further use in a numerical high-frequency simulation model;

– to construct a high-frequency numerical simulation model for diagnosing the insulation of electric machines with multi-turn windings using pulse overvoltage;

– to analyze the results of numerical simulation modeling using a general-purpose induction motor with a squirrel-cage rotor as an example.

4. The study materials and methods

The object of our study is the transient processes occurring in an induction motor with a squirrel-cage rotor and a multi-turn winding of the stator in the induction motor. The studied motor is 4A71B4U3 with a power of 0.75 kW and has 4 sections in the winding phase.

The principal hypothesis of the study assumes the following:

1. Transient processes in the multi-turn insulation that occur when a pulse voltage is applied contain informative features that correlate with the state of the insulation and can be used for its quantitative diagnostics.

2. The parameters of the surge wave change in the presence of defects in the insulation, which make it possible to use transient analysis methods as a sensitive tool for detecting its damage.

3. Pulsed high-frequency insulation diagnostics is a more effective tool for assessing the condition of winding insulation, compared to conventional methods, as it makes it possible to assess inhomogeneities along the entire length of the winding at minimal energy impact.

Assumptions adopted in the study:

1. The insulation of the windings is considered as a heterogeneous multilayer medium with discretely located defects that change the parameters of the electrical signal when the pulse voltage passes through.

2. The shape of the electrical pulse applied to the winding is known, and the influence of parasitic capacitances and inductances of the measurement system does not exceed the permissible level of error.

3. External factors (temperature, humidity, atmospheric pressure, electromagnetic interference, etc.) do not have a significant impact on the diagnostic results.

Simplifications accepted in the study:

1. The geometric shape of the winding is simulated as an idealized linear segmented contour, which makes it possible to simplify the calculation of wave processes.

2. The insulation is considered as a linear, isotropic, and homogeneous medium within each individual layer and the contact of individual turns of the winding.

3. The electrical parameters of the insulation are considered constant during the transient impact of the pulse and along the entire length of the winding. The difference in the capacitive-inductive parameters of the slot and frontal parts of the windings is also not taken into account.

4. The propagation of the pulse signal in the winding is described without taking into account the complex three-dimensional structure of the winding.

5. The phase winding is not represented by a long line with inhomogeneities but by the sum of discrete links with concentrated parameters.

6. The total surge wave does not take into account the difference in processes in the slot and frontal parts of the winding.

7. The model does not take into account mutual inductive couplings between sections of the phase itself, as well as inductive couplings with sections of other phases.

8. The model does not take into account the inductances of the electromagnetic circuits of the sheets of the stacked magnetic core.

The MATLAB Simulink software package (USA) was used for mathematical modeling.

5. Results of research on transient processes in electrical machines with multi-turn windings

5. 1. Theoretical substantiation of the method for solving the problem of constructing a high-frequency numerical simulation model

In the problem of diagnosing the insulation of multi-turn windings in electrical machines based on impulse tests, the correct reproduction of transient processes is decisive. Two approaches are used in the literature:

a) equivalent circuit diagrams in the form of series-connected links, for example, in the form of four-pole ones, with lumped parameters. They correspond to the physical parts of the winding, as a rule, sections of the winding;

b) a long line model with uniformly distributed parameters along the $x \in [0, l]$ coordinate, in which l is the full length of the winding.

For both approaches, the extreme cases are considered: the insulated end of the winding – the no-load mode (NM), and the grounded end of the winding – the short-circuit mode (SC). The corresponding time-space dependences of voltage and current (1), (2) [16] specify the wave pattern of propagation, reflection, and attenuation along the winding $x/l \in [0, 1]$:

$$u(x,t)= =U\left[\frac{H(0)}{V(0)}+\sum_{k=0}^{m-1}\frac{H(-\delta_k)e^{-\delta_k t}}{(-\delta_k)V'(-\delta_k)}+2\sum_{k=m}^{\infty}\mathrm{Re}\frac{H(p_k)e^{p_k t}}{p_k V'(p_k)}\right], \quad (1)$$

$$i(x,t)= =U\left[\frac{H_1(0)}{V(0)}+\sum_{k=0}^{m-1}\frac{H_1(-\delta_k)e^{-\delta_k t}}{(-\delta_k)V'(-\delta_k)}+2\sum_{k=m}^{\infty}\mathrm{Re}\frac{H_1(p_k)e^{p_k t}}{p_k V'(p_k)}\right], \quad (2)$$

where x is the coordinate along the line and takes a value from 0 to l; t is time; $m-1$ is the number of real negative roots $-\delta_k$, and starting from $k=m$, all complex roots are conjugate; p_k are the roots of the characteristic equation:

$$H(p)=Z_2\gamma\,\mathrm{ch}\,\gamma x+(R_0+pL_0)\mathrm{sh}\,\gamma x;$$

$$H_1(p)=\frac{1}{Z_c}\left[Z_2\,\gamma\,\mathrm{sh}\,\gamma x+(R_0+pL_0)\mathrm{ch}\,\gamma x\right];$$

$$V(p)=Z_2\gamma\,\mathrm{ch}\,\gamma l+(R_0+pL_0)\mathrm{sh}\,\gamma l;$$

$$V'(p_{ik})=\frac{d}{dp}V(p)_{|p=p_{ik}};$$

$$U\frac{H(0)}{V(0)}=\frac{1}{\mathrm{sh}\,bl}\left[U_2 shbx+U_2 shb(l-x)\right];$$

$$U\frac{H_1(0)}{V(0)}=\frac{b}{R_0 shbl}\left[U_2 shbx+U_2 shb(l-x)\right].$$

Fig. 1 shows the shape of the voltage pulse applied to the winding of the motor under study [17].

Accordingly, the spatial dynamics of the wave in the winding length–time coordinates are shown in Fig. 2 [17].

When choosing a mathematical apparatus for the analysis of fast transient processes in the windings of electric machines, in particular in the windings of general-purpose induction motors, it is advisable to give preference to the equivalent circuit diagram. The main advantage of this approach is the possibility of transition from a circuit with distributed parameters to a circuit with lumped parameters [16, 18].

The element of the equivalent circuit diagram of the winding of an electric machine is represented by a four-pole in Fig. 3, with the following parameters:

– electrical resistance (R_e) is the electrical resistance of the winding section equivalent to the losses due to eddy currents in the magnetic core of the electric machine;

– inductance (L) is the inductance of the winding section;

– longitudinal capacitance (K) is the total interturn capacitance of the winding section;

– transverse capacitance (C) is the capacitance of the winding section relative to the housing and ground;

– transverse electrical resistance (R_g) – electrical resistance of the insulation of the winding section relative to the housing and ground.

Within the pulse fronts of the microsecond range, the influence of the active resistance of the winding conductors, which in the U-shaped equivalent circuit must be included in series with the inductance. On the first voltage wave, it is secondary to the reactive components, so it can be neglected to simplify the analysis.

Insulation defects can be local and distributed (integral). Local defects are point violations of the insulation structure, which can be complete, that is, having a metal overlap, and undeveloped, that is, with a transition resistance that can change both gradually and abruptly. Integral defects are approximately evenly distributed over the entire volume of insulation.

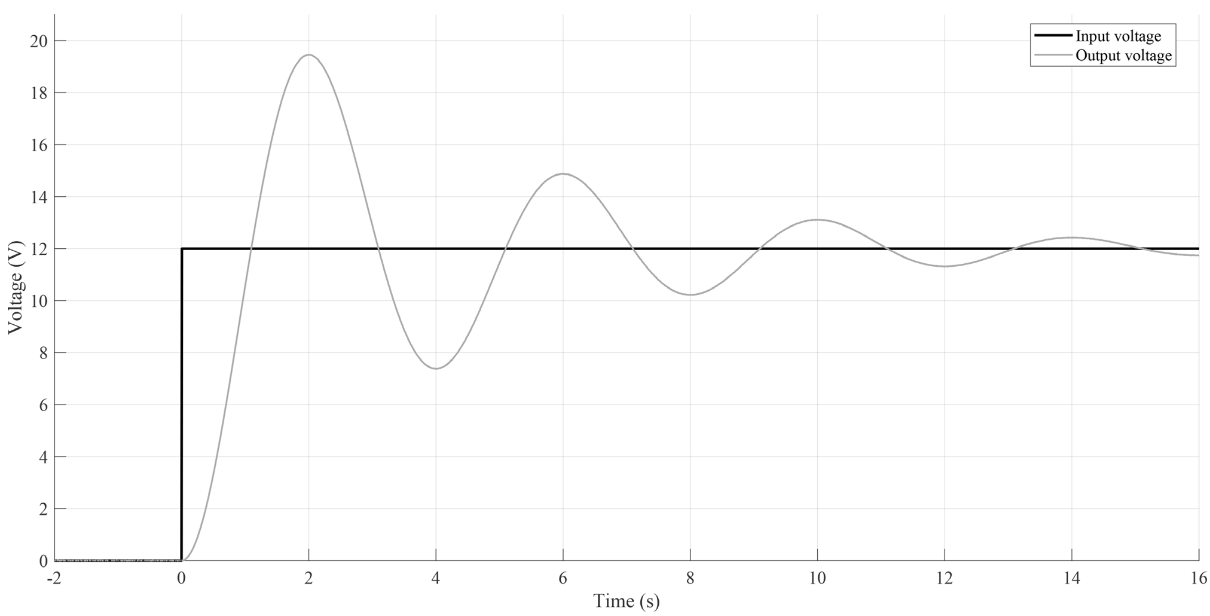

Fig. 1. Input (rectangular pulse) and output (oscillating process) voltage

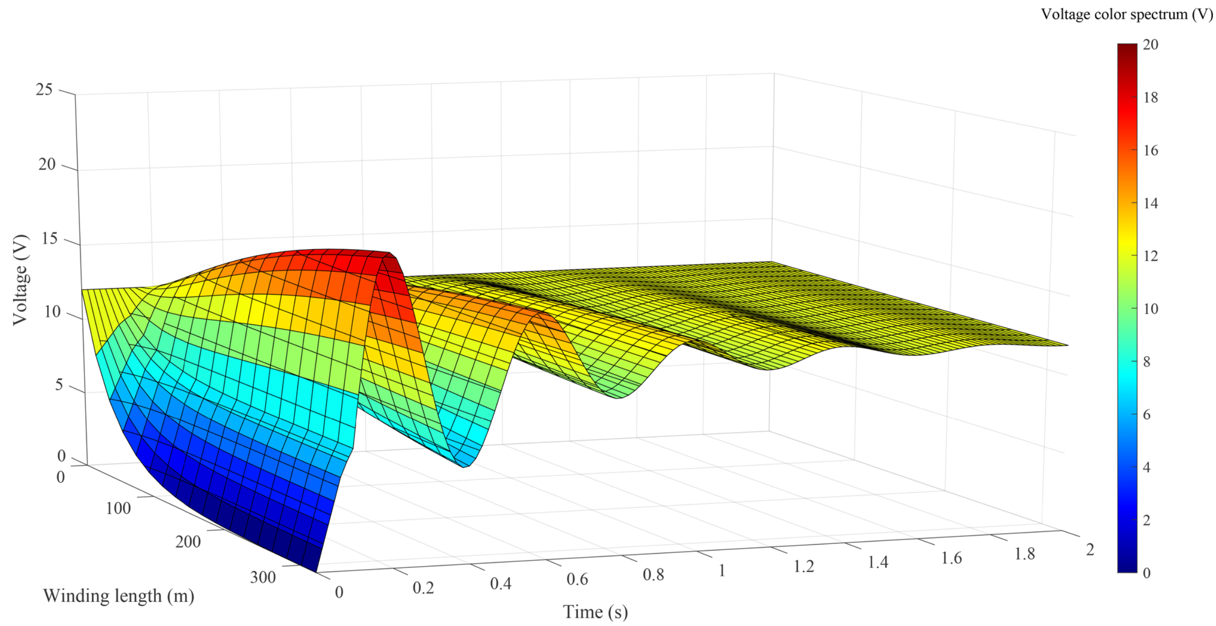

Fig. 2. Propagation of the voltage wave along the length of the winding and time as a response to the application of a rectangular signal

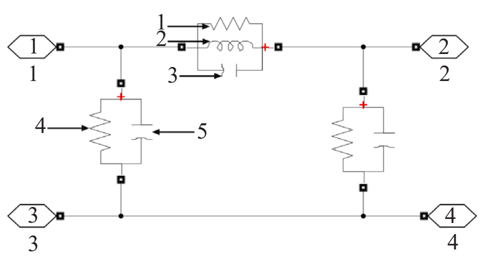

Fig. 3. U-shaped equivalent circuit of the winding in an electric machine 1 – electrical resistance; 2 – inductance; 3 – longitudinal capacitance; 4 – transverse electrical resistance; 5 – transverse capacitance

Integral defects in a multi-link circuit can correspond to a change in the parameters of the equivalent circuit of the transverse capacitance *C* and the longitudinal capacitance *K*. As a rule, this is the result of moistening of aged insulation and at the same time these capacities increase. The same applies to the transverse electrical resistance R_g, which, on the contrary, decreases in the presence of such defects.

Local defects are defects that are specified in each link. Such defects are expressed in a decrease in the inductance of the link *L* and the electrical resistance R_e, which corresponds to a local defect in longitudinal insulation.

This U-shaped element of a distributed electric power transmission line indicates that the winding of an electric machine is a complex structure in which the parameters change depending on the specific length of the winding and the connection scheme.

5. 2. Determining the high-frequency winding parameters for further use in a numerical high-frequency simulation model

The equivalent winding circuit in Fig. 3 reproduces key physical processes and in order for the model to correctly describe the transient and frequency regimes of a particular machine, it is necessary to determine the numerical values of the parameters of this equivalent circuit. According to [19], the first step in determining the parameters is to conduct the amplitude-frequency characteristic (AFC) of a real electric machine.

The scheme of experimental measurement of the amplitude-frequency characteristic of a multi-turn winding under the no-load and short-circuit modes is shown in Fig. 4.

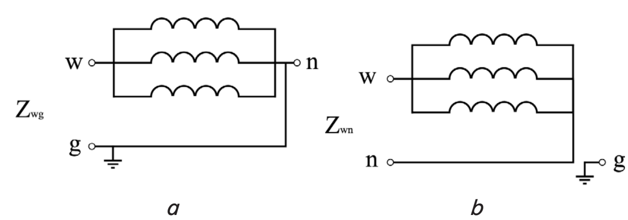

Fig. 4. Schemes for measuring the amplitude-frequency response when connecting three phases in parallel: *a* – short-circuit scheme; *b* – no-load scheme

The experimental amplitude-frequency responses for the circuit in Fig. 4 are shown in Fig. 5.

Having the experimental value Z_{wn}, R_e is determined from expression (3)

$$R_e = 3Z_{wn}. \quad (3)$$

And the experimental Z_{wg} value from formulae (4) makes it possible to determine the transverse capacitance *C* [19]

$$C = \frac{1}{6 \cdot (2\pi f Z_{wg})}. \quad (4)$$

The calculation of the longitudinal capacitance *K* was carried out according to the methodology from [16].

Regarding the transverse resistance R_g, it was measured with a megohmmeter and is more than 1 GΩ, which is actually equivalent to a line break. Given this, in the general case, the equivalent circuit could be simplified and R_g should not be taken into account. However, it was decided to leave R_g as a component of the equivalent circuit since damage to the main (case) insulation leads to a decrease in this resistance. Therefore, accordingly, the presence of the transverse resistance R_g in the equivalent circuit makes it possible to model such defects.

The results of the amplitude frequency response modeling, based on the results of the parameter calculation, are shown in Fig. 6. The results of amplitude-frequency response modeling for simplified circuits consisting of only one winding phase, in contrast to the circuits in Fig. 4, where the winding is represented by three phases, are shown in Fig. 7.

The nature of the obtained frequency response dependences under the short-circuit and long-circuit modes generally corresponds to the well-known theoretical provisions for resonant phenomena in RLC circuits.

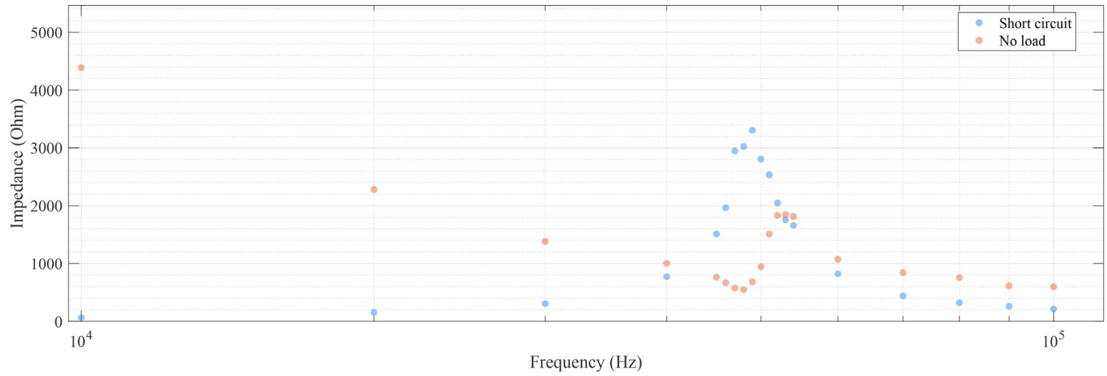

Fig. 5. Experimental amplitude-frequency characteristics: blue dots – short-circuit mode; orange dots – no-load mode

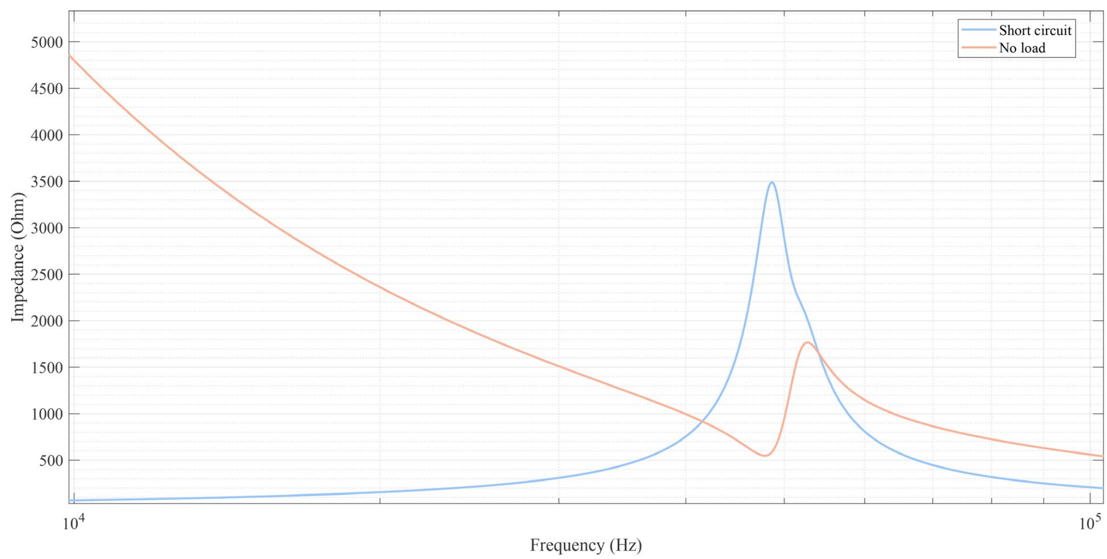

Fig. 6. Modeled amplitude-frequency characteristics: blue line – short-circuit mode; orange line – no-load mode

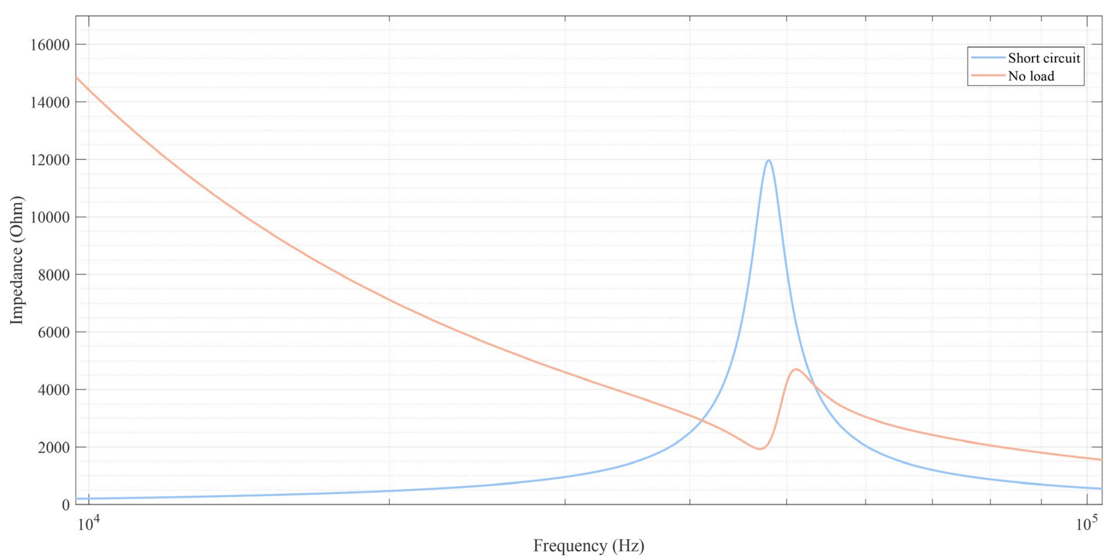

Fig. 7. Modeled amplitude-frequency characteristics for single-phase circuits: blue line – short-circuit mode; orange line – no-load mode

5. 3. High-frequency numerical simulation model for diagnosing insulation of electrical machines with multi-turn windings

From the elements of the equivalent circuit in Fig. 3, an equivalent circuit of the phase winding of the electrical machine was designed, which is shown in Fig. 8, with the designation of measuring points and connections.

Mathematical modeling of single-link and multi-link equivalent circuits was performed by modeling the amplitude frequency response in the range of 10–100 kHz. The results are shown in Fig. 9.

The configuration of the test circuit No. 1 (Fig. 10, *a*) corresponds to the calculation scheme of frequency characteristics with the corresponding high-frequency parameters of the four-poles.

The configuration of the test circuit No. 2 (Fig. 10, *b*) is adapted for the test process of simultaneous comparison of two phases, one of which has heterogeneity.

To verify and refine the high-frequency numerical simulation model, which is planned to be used for a wide class of AC electric machines with multi-turn windings, the amplitude frequency response was recorded on a real induction motor 4A71B4U3.

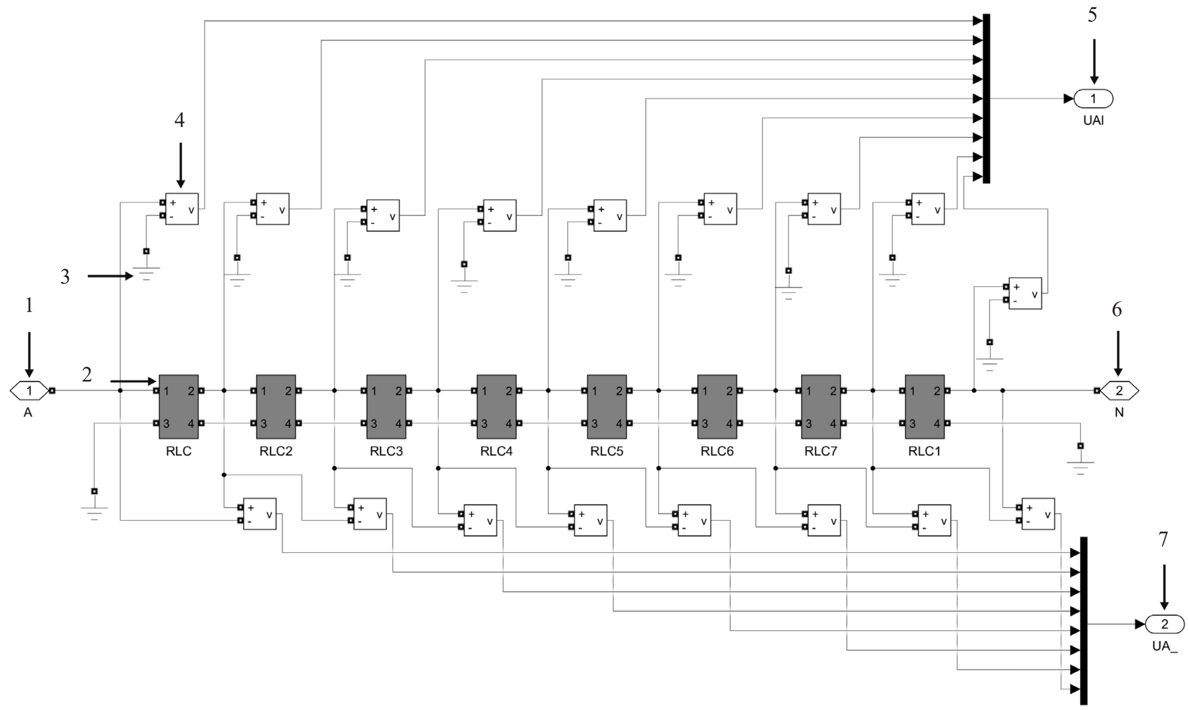

Fig. 8. Equivalent circuit of the winding phase:
1 – terminals of the equivalent circuit; 2 – U-shaped circuit of the equivalent of half of the motor winding section; 3 – grounding; 4 – voltmeter; 5 – terminal for measuring transverse voltage; 6 – terminal to neutral; 7 – terminal for measuring longitudinal voltage

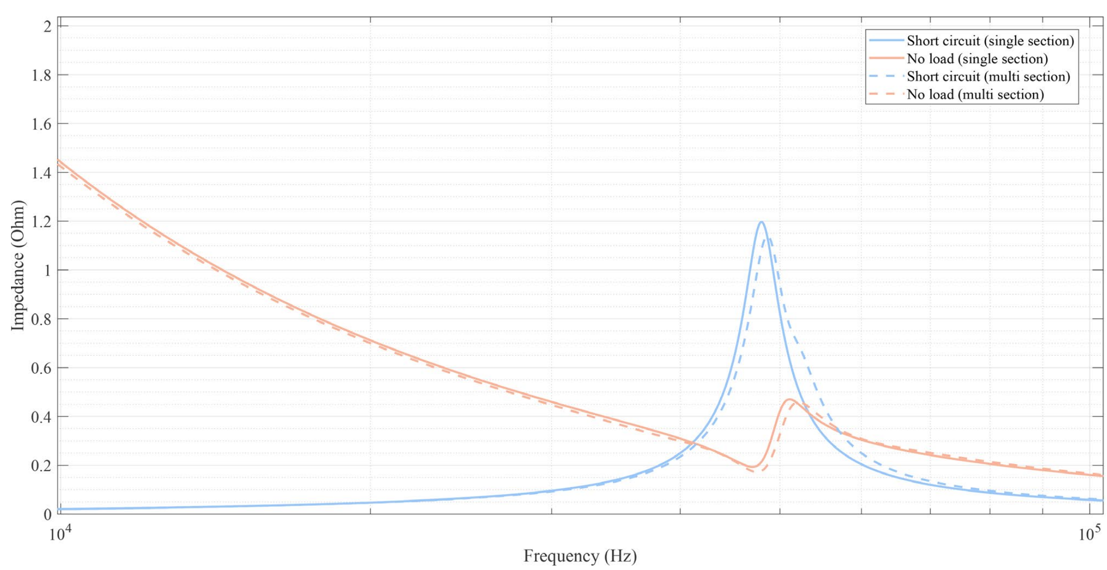

Fig. 9. Modeled amplitude-frequency characteristics: blue lines – short-circuit mode; orange lines – no-load mode, solid lines – single-link circuit; dashed lines – multi-link circuit

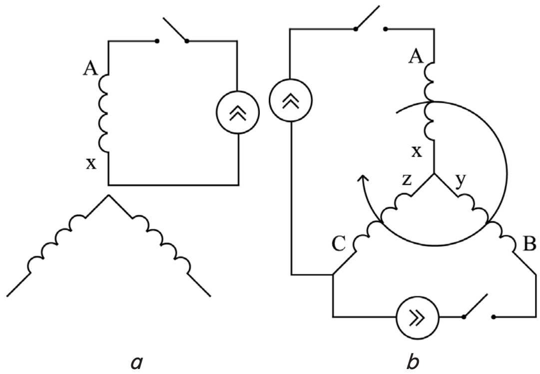

Fig. 10. Test schemes:
a – scheme No. 1; *b* – scheme No. 2

5. 4. Analyzing the results of numerical simulation modeling on the example of a general-purpose induction motor

The results of modeling the transient process caused by the current circuit break in circuit No. 1 under the short-circuit mode, namely the transverse voltage in links 1, 4, and 8, are shown in Fig. 11. In this case, the voltage of link 8 is the voltage before the link, since after link 8 the transverse voltage is 0.

The longitudinal voltage during the same simulation is shown in Fig. 12. The results of modeling the transient process caused by the current circuit break in circuit No. 2 under the short-circuit mode, namely the transverse voltage in links 1, 4, and 8, are shown in Fig. 13.

The longitudinal voltage during the same simulation is shown in Fig. 14.

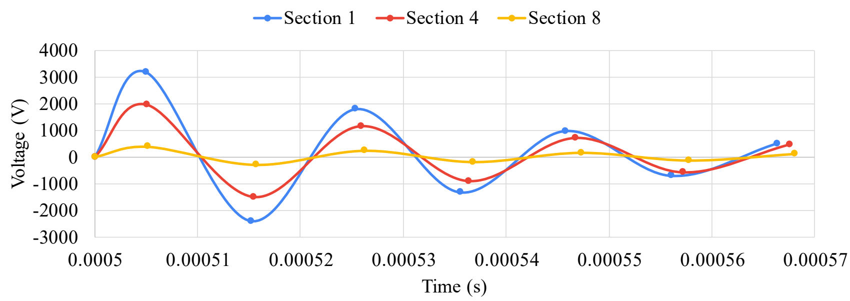

Fig. 11. Transverse voltages of links 1, 4, and 8 during simulation according to scheme No. 1 under a short-circuit mode

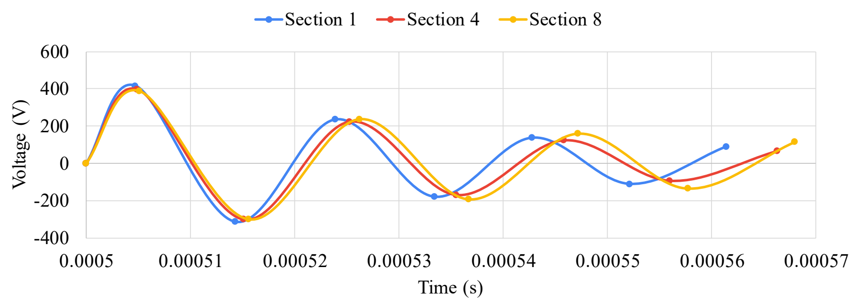

Fig. 12. Longitudinal voltages of links 1, 4, and 8 during simulation according to scheme No. 1 under a short-circuit mode

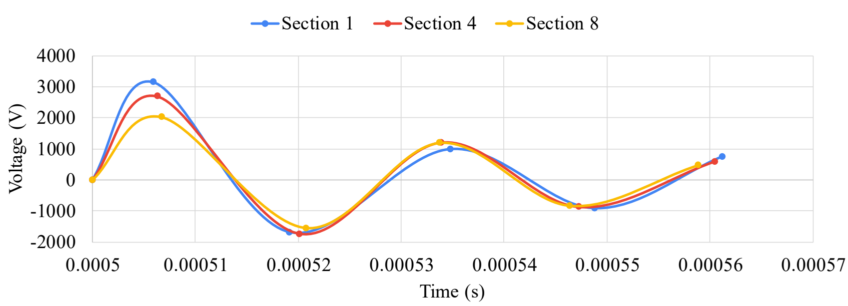

Fig. 13. Transverse voltages of links 1, 4, and 8 during simulation according to scheme No. 2 under a short-circuit mode

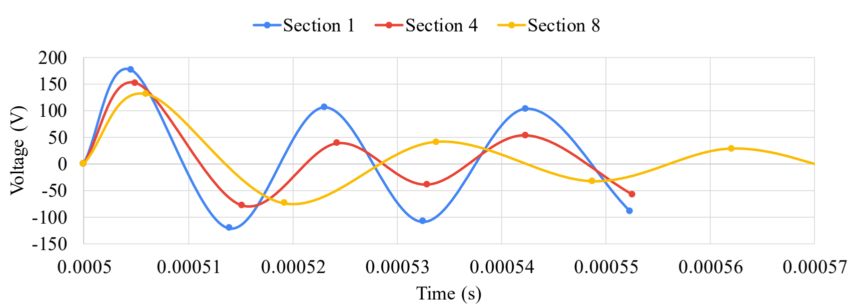

Fig. 14. Longitudinal voltages of links 1, 4, and 8 during simulation according to scheme No. 2 under a short-circuit mode

The simulation data generally reflect the expected results for the distribution of transverse and longitudinal overvoltage when changing the test circuit configuration.

6. Results of research on transient processes in electrical machines with multi-turn windings: discussion

Applying a rectangular voltage pulse to the input of the winding leads to the emergence of an oscillating voltage with reflections at the output, which is shown in Fig. 1. The input voltage has a rectangular shape, and the output voltage is damped oscillations with a natural frequency and decrement determined by the winding parameters. The propagation of the voltage wave along the length of the winding as a function of time as a response to the application of a rectangular signal is shown in Fig. 2 and demonstrates the three-dimensional nature of the wave.

Analysis of processes in a multi-turn winding through long lines is implemented in the algorithms of the MATLAB Simulink software package. The classical theory of a long line is thoroughly worked out in world science, but it does not reflect the entire complex of features and processes inherent in the windings of electrical machines. The winding is not extended in a specific direction but is arranged in a complex manner in the grooves of the magnetic core, which have different primary and secondary parameters in the groove and front parts. Representation of the winding of an electric machine under non-stationary modes by a lumped-parameter circuit also does not reflect the essence of real physical processes. Therefore, a compromise option is to use equivalent circuit circuits that combine elements of the theory of long lines and circuits with lumped parameters, which is implemented using the circuit shown in Fig. 3.

To determine the high-frequency parameters of the winding, the amplitude frequency response was experimentally obtained under two modes. The first mode is with an isolated end of the phase, i.e., under the NM mode, and under the mode with a closed end – under the short-circuit mode (Fig. 4).

According to the obtained experimental amplitude frequency response, which are shown in Fig. 5, all parameters of the equivalent winding circuit are determined and calculated. The inductance of the winding in the equivalent circuit L can be determined by the well-known locked rotor method. The insulation resistance relative to the housing is also experimentally determined. The longitudinal capacitance K, transverse capacitance C, and electrical resistance R_e are calculated according to methodologies from [16, 19]. The data on physical and simulation modeling of the amplitude frequency response show satisfactory convergence of the results.

The study can be carried out both according to a three-phase circuit (Fig. 6) and according to a simplified circuit consisting of only one phase of the winding (Fig. 7), which is confirmed by the sufficient convergence of the frequency response results of these two circuits.

The use of a chain equivalent circuit makes it possible to correlate the number of its links with parts of the winding with the same parameters, for example, a section or half of a phase section. For any arbitrary link, it is possible to introduce heterogeneity, which may correspond to a local insulation defect of varying degrees of development, by modifying the parameters of the four-pole circuit of this link. An additional possibility for improving the analysis of transient processes using the equivalent circuit is to establish the dynamics of the voltage wave propagation along the winding.

Fig. 8 shows that the input impedance of the multi-link circuit is on average 4% less, and the resonant frequency is 2% higher compared to the single-link circuit. Theoretically, the results of the amplitude frequency response calculation should completely coincide for the single-link and multi-link equivalent circuit, but the slight difference in the extremes of the input impedance and the magnitude of the resonant frequency is explained by the above simplifications and assumptions.

The parameters of any studied winding are set in the Simulink model in Fig. 9, on the basis of which transient processes are simulated. In the above calculations, the number of phases of the phase equivalent circuit is taken as $N = 8$. That is, half of the winding section is selected as the equivalent circuit link. We obtain the following values of parameters in the U-shaped equivalent circuit for one link $R = R_{ph} / N$, $L = L_{ph} / N$, $G = G_{ph} / N$, $K = K_{ph} / N$ – where R_{ph}, L_{ph}, G_{ph}, C_{ph} and K_{ph} are the corresponding values of the entire phase.

The test circuits (Fig. 10, *a, b*) were studied under two modes: no-load mode and short-circuit mode. The simplest option is to consider circuit No. 1, Fig. 10, *a*, with modeling of the transient process with the parameters of this process that correspond to the standard overvoltage for low-voltage general-purpose electrical machines $(2U_{nom} + 1000) \cdot 1.41$, i.e., more than 2.5 kV. For circuit No. 1 of the short-circuit mode, during modeling and during experiments, a direct current of 3.9 A was disconnected for 1 μs. Circuit No. 2, Fig. 10, *b*, is more difficult to implement in practice, given the need for synchronous, simultaneous opening of semiconductor switches, as well as synchronous comparison of transients over time in two parallel phases, one of which is likely to have a defect. In the case of this circuit under the short-circuit mode, during simulation and experiments, a direct current of 1.8 A was disconnected in both phases for 1 μs.

Fig. 11 shows that the largest overvoltage falls on the first section, the smallest on the last. Therefore, the voltage distribution relative to the housing is uneven. But this can be partially eliminated by switching the current source to the end of the phase with the corresponding grounding of the beginning of the phase. Thus, the smallest overvoltage will be in the middle of the winding, and it is 65% of the maximum overvoltage. But during operational switching when operating the machine, the ratio of overvoltage at the beginning and inside the winding will approximately correspond to the given ratio.

The data in Fig. 11 are explained by the fact that the gradient of the voltage wave when penetrating deep into the winding decreases and, accordingly, the maximum values of the potentials relative to the housing from the first to the last link of the equivalent circuit decrease. From the point of view of diagnostic tasks, this makes it possible to analyze the probability of an electrical machine failure in the event of insulation breakdown relative to the housing at different locations of the defect.

Fig. 12 shows that the nature of the distribution of longitudinal overvoltage along the length of the winding is significantly different from the distribution of transverse overvoltage. In general, the transient process, as in the previous case, is oscillatory and damped, but the maximum values of the overvoltage on all links are approximately the same. This means that the possibility of detecting weak spots in the interturn insulation along the entire length of the winding is uniform.

The data in Fig. 12 are explained by the fact that the longitudinal voltage on each link is the difference between the transverse voltages at the beginning and end of the link, which is uniform along the winding. In this case, the damping time of the transient process of each link changes, but from the point of view of diagnostics, the absolute values of these voltages are more important. That is, the possibility of detecting weak spots in the winding does not depend on their location.

Fig. 13 demonstrates that the largest overvoltage falls on the first section, the smallest on the last. The transient process changes compared to Fig. 11 because two phases A and C (or B and C) are sequentially turned on instead of one, which leads to a significant change in the capacitive-inductive parameters of the winding, and the distribution of transverse overvoltage changes accordingly. In this case, the ratio of overvoltage between the eighth and first link is 65%. When the phases are circularly switched, this ratio will be maintained for the last section of the winding phase. For the beginning and end of the winding, the picture will be mirrored.

From the point of view of diagnostic tasks, this makes it possible to increase the potentials inside each phase, i.e., the sensitivity to detecting weak points inside each phase increases during circular switching.

Fig. 14 shows that the nature of the distribution of longitudinal overvoltage along the length of the winding is significantly different from the distribution of longitudinal overvoltage according to scheme No. 1. In general, the transient process is oscillatory and damped for all consecutive links but, unlike Fig. 12, there is a greater difference between the maximum values of longitudinal overvoltage of the phase links, and the equivalent frequency of the oscillatory circuit is significantly different, which increases from the first to the last link.

The difference from Fig. 12 is explained by the fact that the conditions for the organization of the surge wave change significantly due to the presence of two current sources in phase A and phase B. These sources are connected in parallel with each other and in series with phase C. In phase C, the initial current doubles. The capacitive-inductive parameters of the entire system also change. From the point of view of diagnostic tasks, it is necessary to take into account the unevenness of this distribution and the influence of the location of the defect.

The use of the proposed approach to diagnosing the insulation of the windings, in contrast to [20], makes it possible to increase the reliability of detecting interturn faults in the winding, especially at the early stages of their development. This becomes possible due to the analysis of the nature of the transient process at different degrees of defects and the comparison of its nature at different switching schemes.

The use of transient processes for diagnosing the multi-turn insulation of the windings makes it possible to detect defects that are at an early stage of development. This directly corresponds to the task of increasing the efficiency of detecting undeveloped damages. High-frequency pulse methods are sensitive to local changes in the insulation structure, which cannot be recorded by conventional methods [21].

The limitations of the proposed method are related to the dependence on the specific type of conductor, laying technology, and design features of the sections, which complicates its unification [22]. The effects of external factors (temperature fluctuations, humidity, electromagnetic interference) can also be imposed, which can significantly affect the accuracy of the diagnostic signal. Our mathematical model takes into account the complex interactions between electrical, thermal, and mechanical processes in a simplified way, which reduces the possibility of full-fledged prediction of insulation resource.

The disadvantages of the study are that our results are mainly based on laboratory tests, which do not fully reproduce the actual operating conditions of electric machines. In addition, the models conditionally take into account the influence of the complex interaction of electrical, thermal, and mechanical processes.

Future studies may involve refining the multiphysics models and taking into account the simultaneous influence of electrical, thermal, and mechanical loads; it is their complex action that affects the insulation life of multi-turn windings. The calculation of the transient process at current switching during the operation of an electric machine is promising.

7. Conclusions

1. The use of a high-frequency method for building a simulation model based on the formation of wave processes in the multi-turn winding sections has been justified. It makes it possible to simulate transient processes in the windings as a response to impulse effects, which distinguishes it from classical methods based on low-frequency effects in which local defects in longitudinal (inter-turn and inter-coil) insulation remain undetected. It also makes it possible to simultaneously diagnose both longitudinal and transverse insulation. Our results are attributed to the high sensitivity and selectivity of wave processes for determining the inhomogeneity of the winding insulation, which makes it possible to detect defects at the early stages of their evolution.

2. High-frequency winding parameters, in particular the wave impedance and distributed capacitances of the sections, which are used to construct a transient simulation model of the winding, have been defined. It is shown that when comparing experimental data and data obtained on the basis of our mathematical model, the relative difference in the basic parameters of the amplitude frequency response, the extrema of the input resistance and the resonant frequency, are 6% and 3%, respectively.

3. A high-frequency numerical simulation model of insulation of electrical machines with multi-turn windings using pulsed overvoltage has been built. The simulation results showed a relative difference in the basic parameters of the amplitude frequency response of 4% for the input resistance and 2% for the resonant frequency, which is quite close. Regarding the analysis of wave processes, the advantage of a multi-link circuit over a single-link circuit is the possibility of modeling defects located in different parts of the winding. This makes it possible to assess not only the fact of damage but also localize the defect location. Taking into account the distributed parameters of the winding sections in combination with the pulsed nature of excitation provides a significant advantage of the proposed method over classical test circuits.

4. Analysis of the modeling results using the example of a general-purpose induction motor revealed that the constructed model makes it possible to detect undeveloped insulation defects of windings at early stages of evolution. We have compared the results from calculating wave processes for different configurations of the test circuit. Test circuit No. 1 makes it possible to obtain longitudinal test gradients that are 2–2.5 times larger with a comparable energy impact. Test circuit No. 2 makes it possible to simultaneously compare two phases, which significantly simplifies the analysis of measurement results.

During the tests, longitudinal overvoltage gradients with a rise front of more than 300 V per 1 μs are formed, which is sufficient for non-destructive breakdown of a defective section of insulation up to 0.1 mm in size. This provides a significant advantage compared to classical insulation testing methods in which such defects are not recorded until the moment of their critical development.

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, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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