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MODELING OF ELECTRICAL AND MAGNETIC TRANSIENT PROCESSES IN A SYSTEM WITH AN INDUCTOR AND A STATOR OF AC ELECTRICAL MACHINES

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Abstract. A brief review of the issue of diagnosing the condition of the insulation structure of electrical machines with classical distributed windings is presented. The rationale and relevance of developing and implementing new, innovative diagnostic and testing methods are provided. The proposed method possesses significant diagnostic features that are absent in other currently used methods. The main difference lies in the creation of high test overvoltages through a rapid change in magnetic fluxes in inductively coupled circuits, one of which is an external sensor-inductor, and the second is a part of the magnetic core with a defective or non-defective winding. A simple and convenient testing scheme is proposed, which can be implemented using appropriate measuring equipment. A comprehensive set of theoretical and experimental studies of the inductor-stator system with a winding was conducted using the Matlab Simulink software package and the field method in a two-dimensional problem formulation in the COMSOL Multiphysics software package. Experimental studies were also conducted on a real sample in the form of a stator of a low-power general-purpose induction motor with a random winding, utilizing the developed testing scheme and device. The theoretical and experimental studies show sufficient convergence of results for engineering purposes. The possibility of achieving test overvoltages exceeding 100 V per turn with low energy impact on defective zones is theoretically and experimentally substantiated, which ensures a minimal destructive effect during diagnostics. Substantial results were obtained for further research and development of the field of insulation condition diagnostics using inductive impulse methods. It is demonstrated that the proposed method will be useful for diagnosing the insulation condition of electrical machine windings in a disassembled state during manufacturing and repair processes.

Keywords: inductive impulse methods, transient processes, winding insulation, electric motor diagnostics.

Introduction. For a long time, diagnostics of electrical equipment has remained a relevant and important field aimed at ensuring reliable operation and high performance characteristics of equipment, reducing downtime losses, and planning measures for improving both individual devices and systems as a whole [1]. At present, insulation testing of windings is largely limited to testing insulation relative to the housing and between phases [2]. At the same time, comprehensive methods for assessing the condition of inter-turn insulation still remain rarely used in electromechanical manufacturing and are almost not applied during the operation of electrical machines [3, 4]. Electric motors with power ratings up to 50 kW are in practice tested only using a megohmmeter and by applying an increased test voltage at industrial frequency [5]. As a result, a certain number of motors are rejected as unequivocally unsuitable for operation due to insufficient strength of their insulation systems.

The primary objective of methods for detecting latent insulation defects, namely inter-turn short circuits, is the identification of local damage at early stages of development [6]. This approach makes it possible to obtain information on the need to prepare for equipment replacement or repair before failure and breakdown occur. Most existing modern methods are based on indirect measurements, such as vibration diagnostics, thermographic inspection, stray field measurements, noise spectrum analysis, and other techniques [7]. In this paper, an induction-based method for diagnosing inter-turn insulation is proposed, which, by means of a special inductor sensor and an electronic commutator, makes it possible to identify not only the damaged phase but also the exact location (slot) of the defect and the defective coil section.

The purpose of the research. To obtain the results of numerical modeling of high-frequency transient processes occurring during rapid current interruption in a circuit with a winding and to compare these results with experimental data.

Object of the research. Experimental and mathematical methods for investigating high-frequency transient processes in electrical RLC circuits with the presence of capacitive and inductive couplings between the equivalent circuits of different windings.

Description of the diagnostic method. The operating principle is based on the law of electromagnetic induction and the equation for electromotive force. In the presence of a inter-turn short circuit within a slot, induced currents are generated in the affected turns by the inductor; these currents, in turn, produce their own magnetic flux, which serves as an indicator of a defect. To measure this flux, a measuring winding is required, at the terminals of which an output signal is induced. The waveform and amplitude of this signal make it possible to draw conclusions about the presence or absence of a defect. In the absence of reference (initial) values, a comparative method with other sections of the winding can be employed. A simplified schematic of the method is shown in Figure 1.

In practice, the magnetic cores of the inductor and the measuring winding should be spaced at a sufficient distance (as far as possible for a specific motor design) in order to reduce the influence of leakage fluxes on the measurement results [8]. The number of turns, as well as the length of the windings, may be either identical or different.

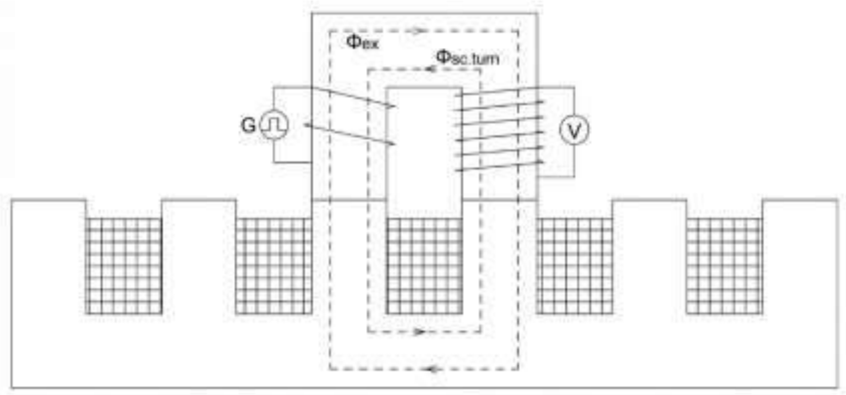

Figure 1 – Operating principle of the induction-based method for detecting inter-turn short circuits

To conduct the experimental studies, a power supply, a controlled short-pulse generator, a specialized measuring device, the stator of an induction motor with a winding, and a two-channel oscilloscope are required. Using this setup, the results presented in Figure 4 were obtained.

Mathematical modeling in MATLAB/Simulink. One of the most widely used software environments for modeling dynamic processes in systems of various physical natures based on linear equivalent circuits is MATLAB/Simulink. One of its main advantages is the built-in Specialized Power Systems library, which contains a large number of standard blocks that enable the analysis of electromagnetic and electromechanical systems of varying complexity [9]. The developed model is shown in Figure 2. The parameter settings of all blocks used in the model are summarized in Table 1.

Table 1. Simulink block parameter settings in the developed model

Parameter	Value
Supply Voltage	13 V
Resistance R3 / Inductance L1	0,1 Ω / 0,2 µH
Winding 1: V1 / R1 / L1	0,3 V / 0,1 Ω /0,1 µH
Winding 2: V2 / R2 / L2	9 V / 0,6 Ω / 0,5 mH
Magnetizing Branch	10 Ω / 0,55 µH
R1, C1 – resistance and capacitance of the primary circuit	1000 Ω / 0,1 nF
R2, C2 – resistance and capacitance of the secondary circuit	2500 Ω / 0,25 nF
Transistor capacitance C3	15 nF
Generator pulse frequency / duration	50 Hz / 200 µs

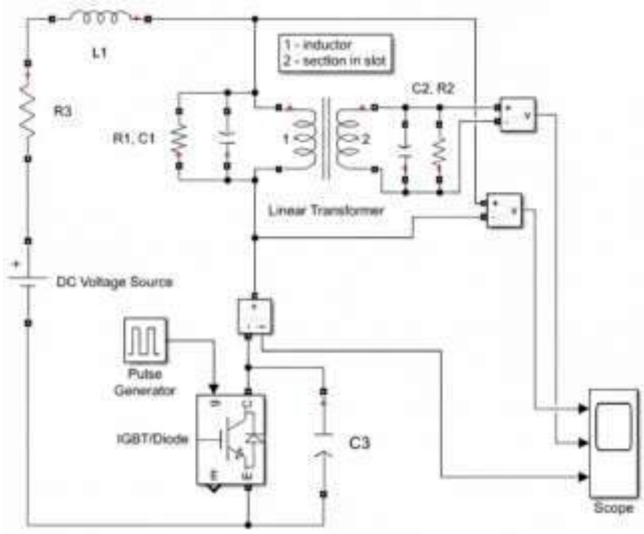

Figure 2 – Constructed model in MATLAB/Simulink

Experimental Studies. A schematic diagram of the experimental setup is shown in Figure 3. A lead-acid battery is used as the power source. The commutator is a specially developed device for regulating the parameters of the current pulse. The inductor sensor consists of an inductor and a measuring module, both fixed along the same axis. To enhance versatility, it is advisable to make one of the magnetic cores with its winding movable, allowing the distance to be adjusted depending on the length of the stator bore of the tested machine. The winding sections of the electric motor are tested using short overvoltage pulses with high amplitude. This primarily tests the strength of the inter-turn insulation. The process occurs by comparing oscillograms obtained for different sections with each other.

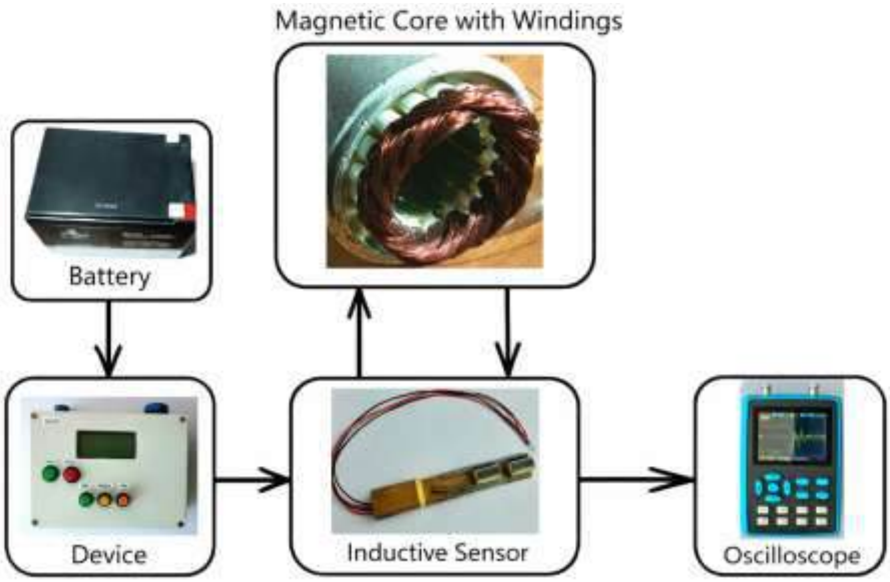

Figure 3 – Schematic of the experimental setup

The developed experimental prototype of the device is built based on an IGBT transistor rated for voltages up to 1200 V and a maximum pulse current up to 120 A.

Thanks to the LCD1604 liquid crystal display and an Atmega328P microcontroller board, the parameters – whose values are adjusted by rotating potentiometers on the front panel – are displayed on the screen. These include pulse duration and frequency. The device also implements the ability to adjust the current cut-off time via the power switch.

Considering the complexity of conducting research on a real induction motor stator and manufacturing a specialized device for it, a simplified model consisting of only two windings – namely, the inductor and one section – was selected for the initial mathematical and physical modelling. As a physical model, a U-shaped magnetic core made of transformer steel with a section and a U-shaped inductor made of the same ferromagnetic material were chosen. The number of turns in the inductor winding is 2, and in the section – 63.

The current value was measured by connecting one channel of a dual-channel oscilloscope to a non-inductive resistor with a resistance of 0.1 Ω. The voltage value was measured using the second channel with a ×100 probe and a maximum signal voltage amplitude of up to 2 kV. If the overvoltage value at the winding terminals may exceed the permissible limit, it is necessary to limit the overvoltage using a varistor or, if possible, gradually increase the overvoltage without abrupt changes.

Figure 4 shows the external appearance of the physical model. Figure 5 presents the oscillograms of transient processes obtained experimentally and from the calculation of the model shown in Figure 2, during rapid current cut-off.

Figure 4 – Physical model of the inductor and stator section

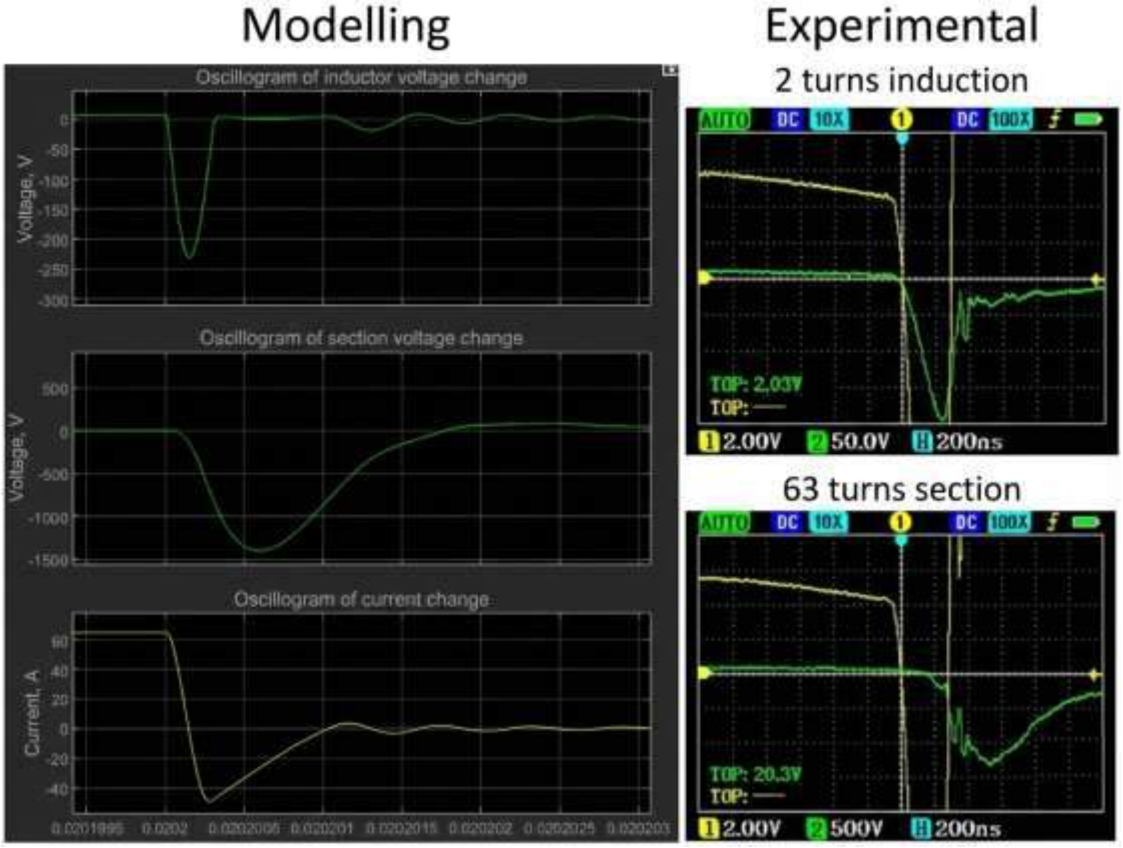

Figure 5 – Obtained oscillograms of transient processes in the windings

As can be seen in both cases, the duration of the overvoltage pulse at the section terminals in the slot is longer than the duration of the pulse at the inductor winding terminals. Thus, it can be concluded that the coil with a larger number of turns has a lower resonant frequency and a longer half-period duration of the sinusoid. In addition, the voltage amplitude values for the inductor winding and the section in the experimental and calculated variants differ insignificantly, which further confirms the correspondence of the constructed equivalent electrical circuit and model to the real physical system. Therefore, the obtained model can be used for further calculations of similar systems. The proposed model can subsequently be refined and modified depending on the objectives and specifics of the research.

Modelling Using COMSOL Multiphysics. The most versatile and powerful tool for modelling electrical and magnetic physical processes in electromechanical systems is the field and coupled field-circuit methods, the calculations of which are implemented in COMSOL Multiphysics [10]. The advantage lies in obtaining two-dimensional or even three-dimensional distributions of electric and magnetic fields, which allows investigating the influence of geometry and local processes. The disadvantage is the need for high computational power and large memory volume for storing results. As a consequence, such studies require a significant amount of time and demand a high level of researcher preparation, understanding of the principles for constructing complex models, and tuning optimal calculation parameters depending on the task at hand [11]. For this reason, the calculation was performed for a two-dimensional problem formulation. This approach introduces certain errors; however, given the low influence of end effects in the system under study, the obtained results have sufficient accuracy for practical application.

Rectangular current pulses with a frequency of 5 kHz were specified using a constant component and a series of sinusoids of different frequencies, namely the odd harmonics up to the fifteenth relative to the fundamental frequency of 5000 Hz [12]. The obtained current pulses are shown in Figure 7. The equation for the time variation of the current has the following form:

$$I = 50 + 62 \cdot \sin(\omega \cdot t) + 19 \cdot \sin(3 \cdot \omega \cdot t) + 9.8 \cdot \sin(5 \cdot \omega \cdot t) + 5.4 \cdot \sin(7 \cdot \omega \cdot t) + 3 \cdot \sin(9 \cdot \omega \cdot t) + 1.5 \cdot \sin(11 \cdot \omega \cdot t) + 0.75 \cdot \sin(13 \cdot \omega \cdot t) + 0.55 \cdot \sin(15 \cdot \omega \cdot t) \quad (1)$$

Figure 6 shows the obtained distributions of magnetic induction and current density in the cross-section of the active part for a pulse duration of 100 µs and a current cut-off time of 10 µs. On the left are the distributions for the case of an undamaged section in the slot. On the right is the damaged section with five short-circuited turns. The model accounts for the influence of the steel magnetization curve on the results. The calculation time was selected from 0 to 500 µs with a step of 1 µs. This ratio is optimal for simultaneously obtaining results of sufficient quality while saving the limited computational resources of the computer and model calculation time. The finite element mesh density is Coarse.

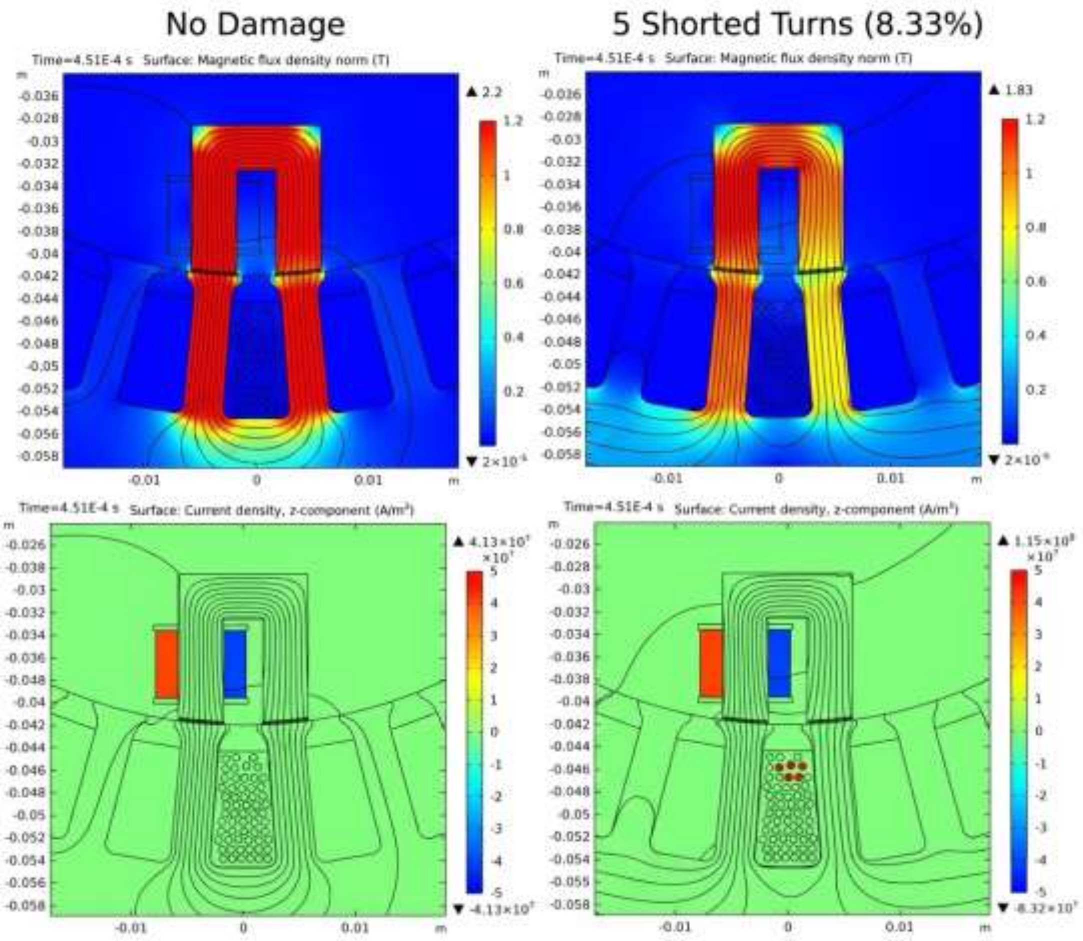

Figure 6 – Distributions of magnetic induction and current density without damage and in the presence of a inter-turn short circuit of 8.33% (5 turns out of 60)

Comparing the obtained results, a significant influence of the presence of five short-circuited turns on the distribution of magnetic induction in the cross-section of the active part is noticeable. Its value substantially decreased from approximately 1.3 T to 0.9 T. Such a significant change in the magnetic flux in the core can be relatively easily detected in practice using a measuring winding.

To compare the obtained overvoltage values on the inductor winding and to obtain the time distribution of the current induced in the damaged turns, graphs based on the calculated data are constructed and shown in Figure 7.

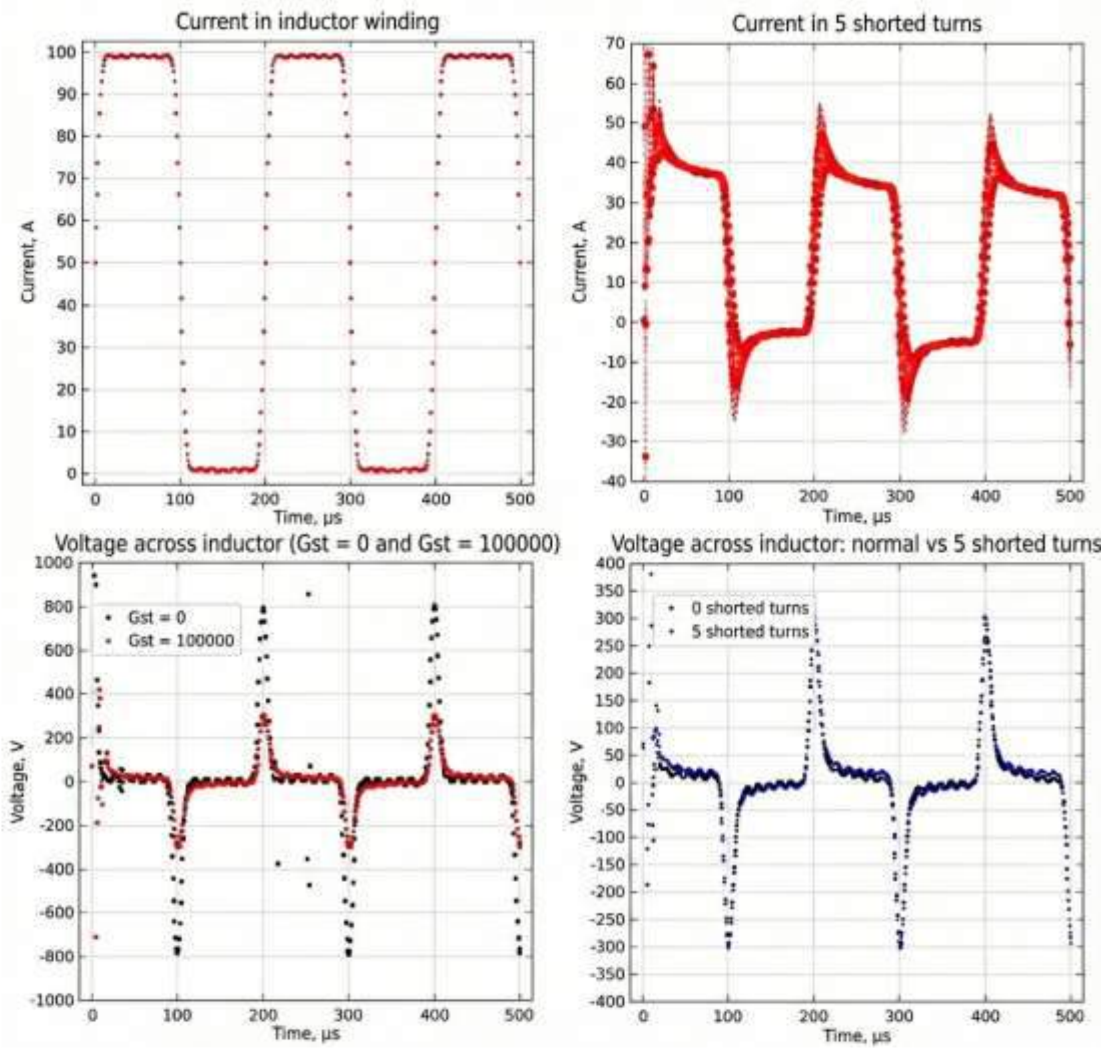

Figure 7 – Results of the study of the influence of defects on transient processes

After analysing the obtained data, the following conclusions can be drawn. First, the shape of the induced voltage curve in the short-circuited turns has a predictable appearance, namely a sharp rise to the maximum value at the beginning of the transient process and gradual decay over a time of 100 µs. According to the obtained results, this time is insufficient for complete current decay. The maximum value of both the induced current and the overvoltage at the inductor winding terminals coincides with the moment of the highest rate of change of the inductor winding current, which corresponds to the previously obtained data by other methods described in this work.

Second, the presence of eddy currents in the magnetic core significantly reduces the overvoltage amplitude, while the presence of short-circuited turns has an insignificant effect on the maximum voltage amplitude at the inductor winding terminals. In this case, only the amplitude changes, while the pulse shape remains unchanged. This result generally corresponds to the experimentally obtained data, and the deviations are associated with the simplification of the model itself.

Thus, the results of modelling in COMSOL Multiphysics confirm the operability of the proposed approach based on the impact on turn insulation through sharp changes in current and the magnetic flux linked with it.

Conclusions. In this work, a comprehensive study of transient electrical and magnetic processes in a system consisting of the stator of an electric motor with a distributed random-wound winding and a special inductor with a low-turn winding and a high current slew rate was carried out.

The main result is that the obtained overvoltage values exceed 100 V for a part of a section with an underdeveloped defect and reach up to 1.3 kV at the maximum, which is limited by the breakdown voltage of the switching transistor. These overvoltages make it possible to detect not only metallic short circuits but also latent insulation defects at early stages of their development. A distinctive feature of this study is the simultaneous investigation of the system using three approaches: experimental measurements, numerical modelling in MATLAB/Simulink, and field-based methods implemented in COMSOL Multiphysics. As a result, the most comprehensive picture of processes of different physical natures occurring in the investigated system was obtained.

The results show that, in Figure 5, the experimental and calculated data exhibit fairly high agreement, which confirms the accuracy of the developed mathematical model. The results obtained using the field method show certain discrepancies, which are associated with specific features of model development and calculation. The main reasons are the neglect of capacitive couplings between structural elements and the discrepancy between the assumed and the actual current waveform, introduced to simplify the modelling procedure. To obtain results closer to real operating conditions, it is necessary to develop a multiphysics circuit – field model with an increased number of calculation steps. Such an approach requires substantial experience and significant computational resources to solve complex models of this type. Nevertheless, the obtained results are sufficient to confirm the occurrence of overvoltages with magnitudes close to the experimentally observed values, as well as the significant influence of eddy currents in the magnetic core on the overvoltage level, which is clearly illustrated in Figure 7 (lower left corner).

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