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HIGH-FREQUENCY PROCESSES IN THE WINDINGS OF GENERAL-PURPOSE ELECTRICAL MACHINES IN THE PRESENCE OF DEFECTS IN THE GROUND-WALL INSULATION

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Insulation defects in general and ground-wall insulation problems in particular are one of the main causes of failure in general-purpose induction motors. Most of the articles on this topic focus on more complex, expensive and comprehensive diagnostic methods, but they are not always appropriate and justified for electric machines of small and medium power, which are widely used in the agricultural sector. This article deals with the relevant problem of ground-wall insulation diagnostics. Namely, the development of such a diagnostic technique, which would not be resource-intensive, would not require complex equipment and would be easy to use.

It has been verified that the use of a single-link replacement scheme for high-frequency testing can indicate the presence of a ground-wall insulation defect in a particular winding phase, but cannot be used for more detailed analysis, for example, to locate the defect.

It is shown that when using a multilink replacement scheme, it is possible to model the damage to the ground-wall winding insulation when defects of different level are located along the entire length of the winding at the level of one coil. High-frequency tests were performed in this mathematical model and data were collected, namely the resonant frequency and input impedance at resonance, for defects of different degrees at different locations in the winding in the short circuit and open circuit modes. In parallel with the mathematical modeling, the resonant frequency was calculated using engineering formulas to control the results of the mathematical model.

A number of experimental studies were also conducted on a specially prepared sample of a real 4A90L2 engine to verify the convergence of the mathematical modeling results with real experimental data. The experimental data confirm the adequacy of the model, and the results differ by no more than 5-7%, which indicates that the mathematical model is sufficiently accurate.

As a result, a specific algorithm for implementing the method of detecting defects in the ground-wall insulation of multi-turn low-voltage electrical machines for general-purpose use by means of high-frequency effects by analyzing the input resistance and resonant frequency when comparing defective and defect-free phases in symmetrical three-phase windings is proposed. The proposed method makes it possible to determine the presence of a local or integral defect in the ground-wall insulation. In the case of a local defect, it makes it possible to determine the location of the defect down to the level of the winding coil. This method can also partially indicate the presence of defects in the longitudinal insulation.

Key words: *input impedance, resonant frequency, amplitude-frequency and phase-frequency characteristics, winding insulation defects, multi-line substitution scheme.*

F. 5. Fig. 14. Ref. 18.

1. Problem formulation

The development of technologies and increase in the productivity of agricultural and agricultural enterprises cannot be imagined without increasing the use of electric machines (EM). Which requires solving the problems of reliability and durability of electrical equipment operated in specific conditions of agricultural production. The main consumer of electricity in agriculture is electric motors, the smooth operation of which depends on the normal functioning of any technological process.

The main EMs used in agriculture are squirrel-cage induction motors (IMs) [1, 2], which are generally very reliable. However, level of structural reliability of AC motors are not achieved in agriculture. The high failure rate of IM motors is due to the multifactorial impact on the EM from a complex agricultural production system.

Large enterprises such as poultry farms, livestock farms and feed mills have a large number of EMs that are part of the overall life support system of living organisms. Failures of IMs in such systems lead not only to direct damage associated with the cost of replacing and repairing the failed equipment, but also to technological losses due to reduced productivity and even animal death.

The operation of EM with an almost exhausted insulation resource usually leads to its rapid destruction, which can cause significant damage to the entire production process associated with the operation of the machine with a defect. First of all, this applies to the insulating structure of the machine, which is gradually destroyed under the influence of thermal and mechanical stress, moisture, switching overvoltage, etc. Therefore, timely detection and identification of insulating structure defects is an actual task.

The process of formation of an insulation defect is slow at first, but in the last stages, sudden physical phenomena occur, which usually result in a short circuit (SC) of the insulation to the machine body or the insulation of turns or coils among themselves [3]. The formation of a conductive breakdown channel can be represented as a transient resistance that decreases according to a certain law over time and can be represented as an electrical active resistance.

Also of interest is the identification of insulation defects in multi-turn coils, which can be divided into integral and local defects in the insulating structure. Integral defects are characterized by general aging of the insulation, which is expressed in the loss of insulating quality of the interconductor dielectric layer in the form of cracks, punctures, cavities, which are distributed evenly throughout the entire insulation. In the case of EM ground-wall insulation, integral defects can be expressed in the form of a decrease in the interphase insulation resistance and phase-to-body insulation resistance. For longitudinal insulation, i.e., inter-turn and inter-coil insulation, they are expressed in the SC of one turn or a group of turns or to a certain transient resistance. Conventionally, insulation defects can be divided into transverse insulation defects (ground-wall and interphase) and longitudinal insulation defects (inter-turn and inter-coil). This study is concerned with the detection of local defects in the ground-wall insulation in a particular coil and the separation of these defects from integral ones.

In addition to integral defects, local insulation defects, i.e. short circuits or transient winding-to-body resistance, and interphase local defects, as well as local defects in the form of complete or incomplete overlaps between individual windings and between coils of the same phase, pose a greater danger [4].

2. Analysis of recent research and publications

Paper [5] proposes a certain on-line monitoring with subsequent analysis to determine the state of insulation and predict how much longer the EM can operate without repair. Such monitoring is not financially feasible for low- and medium-power EMs.

The article [6] mentions different approaches to diagnostics, but focuses on the partial discharge diagnostic approach. Different partial discharges are considered for different types and powers of EM, as well as different insulating materials.

Article [7] suggests applying a direct current for a certain time, sometimes more than an hour, and taking the winding resistance value and determining the polarization index. Such studies are not always possible and justified, and non-destructive diagnostic methods have their advantage in this regard. The article focuses on methods of data collection and analysis, and does not offer methods of defect localization.

Paper [8] focuses on low-voltage, high-performance machines with short operating times. A model for assessing the winding condition is proposed here. The experiments and the model prove that when analyzing such EMs, it is necessary to take into account not only thermal aging, but also thermo-mechanical aging, i.e., variable load and on/off cycles.

Reference [9] provides an overview of approaches to analyzing the state of various EM components. It is confirmed that insulation in general, and grounding insulation in particular, is a frequent cause of EM failure. When reviewing the methods, they focus on diagnostics using partial discharge, which is not always justified by the complexity and high cost of the methodology for low and medium power EM.

[10] is a review article that discusses diagnostic and both on-line and off-line monitoring methods. Diagnostic methods such as polarization/depolarization current measurement, dielectric spectroscopy, and operational leakage current monitoring are considered. These techniques are not easy and quick to perform.

In [11, 12], substitution schemes are proposed for high-frequency modeling and have an analysis of resonant impedance. However, they do not suggest ways to localize defects in the case insulation and ways to model such defects in the replacement scheme.

The aforementioned articles confirm that diagnostics of the condition of the ground-wall insulation is an important part of the overall EM diagnostics. At the same time, the articles mainly offer more complex diagnostics that require more time, sophisticated equipment, have a higher complexity of the diagnostics itself, or are non-destructive, although they are more versatile, comprehensive and can be more accurate. Therefore, the development of a methodology for the study of ground-wall insulation that would be easy to perform, not require much time, complex, expensive equipment, be non-destructive and not require lengthy data analysis, which, accordingly, makes it possible to use it for low and medium power EM is an actual task.

3. The purpose of the article

The purpose of the article is to organize the test process using high-frequency methods for diagnosing the ground-wall insulation of low-voltage EMs of low an medium-power general-purpose by identifying possible diagnostic features and proposing a methodology for assessing the development of defects and their location at the level of localization of the damaged coil of the winding phase.

4. Results of the researches

The study of EM operation and an overview of switching, wave and pulse processes requires a mathematical description of the winding. In general, a real winding is a complex system. It is heterogeneous, since the turns of even one coil have different parameters depending on the position in the groove. In addition, within the same coil, the specific parameters of the active and frontal parts differ. The transition from one coil to another is obvious, i.e., the system is discrete and heterogeneous. Therefore, the presentation of the winding as a long homogeneous line with distributed parameters will give significant errors when examining the processes in the middle of the winding. However, a similar model with averaged parameters can be used to estimate input and wave impedances [13].

It is known that insulation defects can be detected using transient processes, such as impulse and high-frequency processes [15-17]. For example, when taking the frequency characteristics of three-phase symmetrical windings with the subsequent comparison of the essential parameters of high-frequency phenomena that indicate the presence, development, and location of defects. The diagnostic features include such parameters as the input winding impedance when the frequency changes in the range from 0 Hz to 1 MHz, and the resonant frequency. These parameters are determined by the ratio of the winding's active-inductive and active-capacitive parameters when the frequency changes. In the presence of defects of varying degrees of development, as well as different locations, the ratio of these parameters changes significantly, which, in comparison with defect-free phases, can serve as a diagnostic sign.

According to the circuit theory [14], when the active resistance R and inductance L are connected in series in a longitudinal quadrupole, the first resonant frequency of the winding can be determined by the expression:

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{GR + \left|P_1^{(0)}\right|}{(C + \left|P_1^{(0)}\right| * K)L} - \left(\frac{C}{2(C + \left|P_1^{(0)}\right| * K)} + \frac{R}{2L}\right)^2}, \quad (1)$$

where R – longitudinal active resistance; L – longitudinal inductance; K – longitudinal capacity; G – ground conductivity; C – transverse capacity. $P_1^{(0)}$ in this formula is the so-called eigenvalues of the winding in the open circuit (OP) mode. This is a dimensionless value corresponding to the first "zero" in the OC mode and characterizing the first resonant state in a homogeneous circuit. Eigenvalue $P_1^{(0)}$, like all other eigenvalues of the winding, does not depend on the specific structure of the substitution circuit link, but is determined only by the number of links and can be represented as follows:

$$P_1^{(0)} = -4sin^2\frac{\pi}{4\upsilon}, \quad (2)$$

where υ – the number of links. Assume that the longitudinal capacitance of the coil is very small, as is the case, for example, in high-voltage machines, so it can be assumed $K \approx 0$. Thus, the formula for the first resonant frequency is simplified to the following form:

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{GR + \left|P_1^{(0)}\right|}{CL} - \left(\frac{1}{2} + \frac{R}{2L}\right)^2}. \quad (3)$$

The expression always holds for EM windings:

$$\frac{GR+\left|P_1^{(0)}\right|}{CL} \gg \left(\frac{1}{2}+\frac{R}{2L}\right)^2, \quad (4)$$

therefore, the square of the value in brackets in equation (3) can be neglected, and the formula for the first resonant frequency will be as follows:

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{GR+\left|P_1^{(0)}\right|}{CL}}. \quad (5)$$

As can be seen from equation (5), the value of the first resonance frequency largely depends on the value of the eigenvalue of the winding, and, accordingly, on the number of links of the phase winding. In addition, although to a lesser extent, the value of the resonance frequency depends on the secondary wave parameters – R, L, C, G and, above all, the longitudinal capacitance K.

For the case considered in this article, the longitudinal capacitance should be taken into account, because in multi-turn coils, which are typical for low- and medium-power machines, it is commensurate with or exceeds the transverse capacitance. For more powerful machines, from 37 kW, the influence of the longitudinal, i.e. inter-turn and inter-coil capacitance K is insignificant. For the 4A90L2 motor, which was the object of our study and for which the experimental frequency characteristics were taken, the resonance frequency according to formula (1) is 76 kHz, which is a slight deviation. In the experiments, this formula approximately determines the resonance frequency at defects of varying degrees, i.e., 0.5, 0.2, 0.1, 0.05 MΩ. This formula can be used in the qualitative evaluation of high-frequency processes modeled by a single-link scheme, which corresponds to the transformation of a multi-link substitution scheme into one quadrupole with concentrated parameters. The calculated resonant frequency according to formula (5) for a strongly developed defect with a transient resistance of 50 kΩ is 73.6 kHz. That is, when using a single-circuit circuit, the development of the defect can be estimated with an accuracy of up to 10% of its real transient resistance, but its location cannot be established.

In [11, 12, 18], the high-frequency process was considered on the example of a multi-link substitution circuit consisting of quadrupoles with concentrated parameters. Each quadripole corresponds to a part of the winding phase. In this article, the study concerns a specific 4A90L2 motor with phase coil leads to the external panel. The defects in the ground-wall insulation were physically modeled by connecting the coil leads through a certain resistance to the motor body. The connection of the coil lead to the body directly corresponds to a complete phase breakdown to the body. The resistances were set as a series of defects of varying degrees of severity, i.e., 0.5, 0.2, 0.1, 0.05 MΩ. These transient resistances were connected alternately to the phase coil terminals from the beginning to the end. It is of considerable interest to determine, using the proposed high-frequency method, the location of the defect at the level of the part of the winding corresponding to the quadrupole with concentrated parameters.

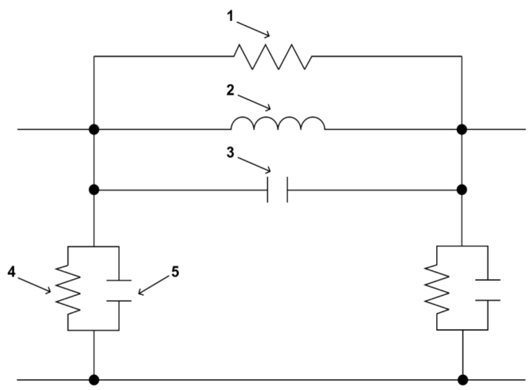

Fig. 1. Schematic substitution diagram of winding section

The diagram (Fig. 1) shows a link in the form of a quadrupole consisting of the following elements: 1 – longitudinal active resistance; 2 – longitudinal inductance; 3 – longitudinal capacitance; 4 – resistance corresponding to the insulation resistance relative to the body and ground; 5 – winding capacitance relative to the body. By changing the resistance to the body, defects in different parts of the winding can be modeled.

The following assumptions are made in the proposed link substitution scheme:

1) we neglect the active resistance of the winding phase;
2) the parameter C of the capacitance is considered constant over the entire frequency range;

3) the parameters L and R are calculated for the resonant frequency and are considered constant in other frequency regions.

In the course of the research, a program was developed to calculate high-frequency processes in the motor under study, which, according to experimental data, has the following phase parameters: $R_{ph} = 14.3\,kOhm$ – longitudinal active resistance of the phase; $L_{ph} = 9 * 10^{-3}\,H$ – longitudinal inductance of the phase; $K_{ph} = 1.452 * 10^{-12}\,F$ – longitudinal capacitance of the phase; $R_{cph} = 500\,MOhm$ – phase resistance, which corresponds to the insulation resistance relative to the body and ground; $C_{ph} = 1.2 * 10^{-9}\,F$ – winding capacitance of the phase relative to the body.

The number of coils in the phase of this motor that are connected in series is 6. Therefore, the substitution circuit consists of six links, each of which is defined as follows: $R = R_{ph} / 6$ – longitudinal active resistance of the link; $L = L_{ph} / 6$ – longitudinal inductance of the link; $K = K_{ph} * 6$ – longitudinal capacity of the link; $R_c = R_{cph} * 6$ – resistance, which corresponds to the insulation resistance of the link relative to the body and ground; $C = C_{ph} / 6$ – capacitance of the link winding relative to the body [14].

Frequency response (FR) and phase response (PR) of a defect-free 4A90L2 engine in the SC (Fig. 3) and OC (Fig. 4) modes are given, calculated on the basis of a multi-link substitution scheme (Fig. 2).

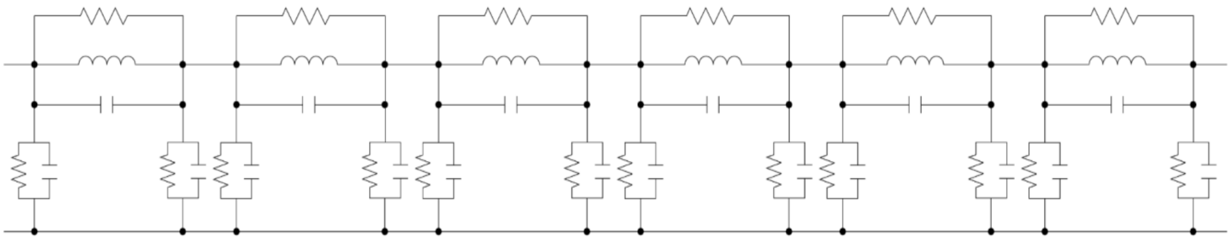

Fig. 2. Schematic diagram of a multi-link winding phase replacement for six coils

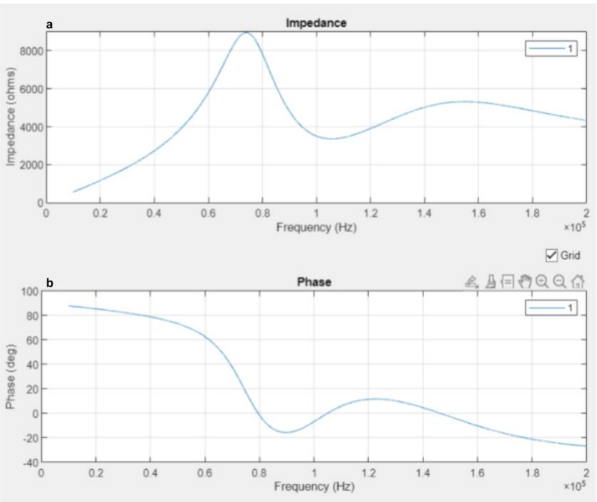

Fig. 3. FR (a) i PR (b) in SC mode

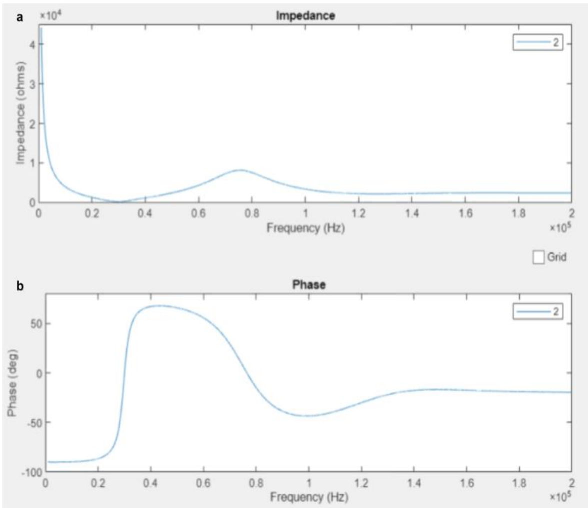

Fig. 4. FR (a) i PR (b) in OC mode

At the same time, a simplified single-link substitution scheme corresponding to a quadrupole with concentrated parameters was also investigated for the qualitative study of physical processes.

Next, in the multi-link replacement circuit, we set the defects to 0.5, 0.2, 0.1, 0.05 MΩ. We have six coils in phase connected in series. We set the specified defects in each coil in turn, noting the input impedance and resonance frequency. We compare the results with a defect-free winding. In a real test setup, the damaged phase is compared with a defect-free phase, given that the three-phase winding is symmetrical and has the same output parameters. The possibility of the same defects occurring in all phases is considered unlikely. The results and comparisons are shown in Figs. 5, 6.

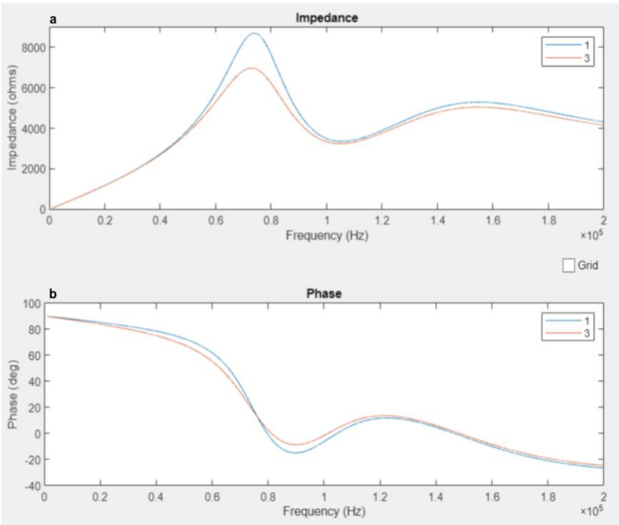

Fig. 5. FR (a) і PR (b) in SC mode for a defect of 0.5 MΩ (1) and a defect of 0.05 MΩ (3)

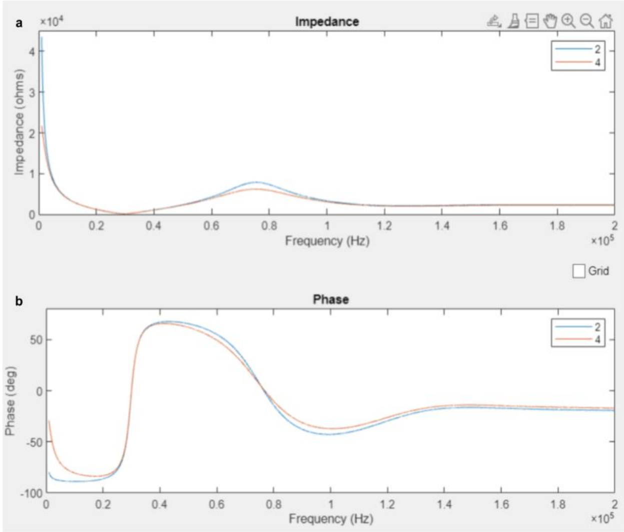

Fig. 6. FR (a) і PR (b) in OC mode for a defect of 0.5 MΩ (2) and a defect of 0.05 MΩ (4)

The input impedance has changed significantly and the frequency has changed slightly. Next, we place the defects in each link, sequentially from the first to the sixth, and take the FR in the SC and OC modes (Figs. 7-14). We also present experimental data for a defect of 0.5 MΩ and 0.05 MΩ (Figs. 7, 8, 13, 14). The difference between the experimental data and the results of mathematical modeling can be partially explained by the assumptions made in the mathematical modeling.

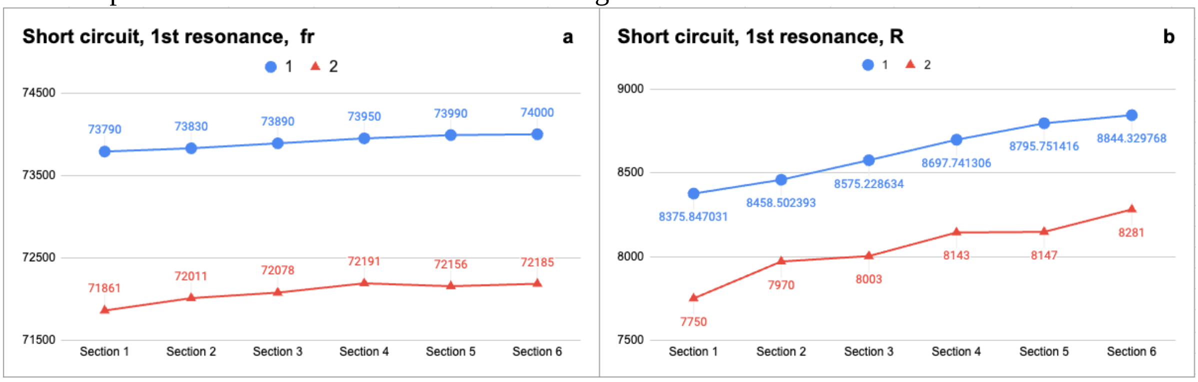

Fig. 7. The FR results in SC mode: a) – resonant frequency; b) – input impedance when one of the links has a resistance relative to the case of 0.5 MΩ, model results (1) and experimental results (2)

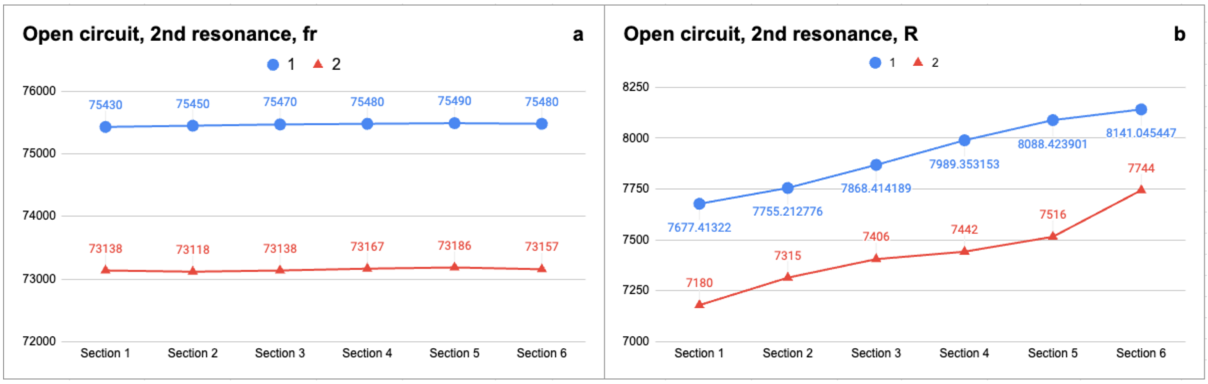

Fig. 8. The FR results in OC mode: a) – resonant frequency; b) – input impedance when one of the links has a resistance relative to the case of 0.5 MΩ, model results (1) and experimental results (2)

The nature of the resistance distribution depending on the location of the defect has an almost linear increasing character (Fig. 7, b) as the defect location approaches the end of the phase. At the same time, the percentage difference in the resistance of the first and sixth winding coils is 5.6% in the case of SC (Fig. 7, b) and 6.04% in the case of OC (Fig. 8, b), which is quite easy to measure with modern devices. The relative difference in the resonant frequency of the first and sixth sections is 0.2% in the case of a SC (Fig. 7, a) and 0.06% in the case of OC (Fig. 8, a), which is much smaller compared to the input impedance.

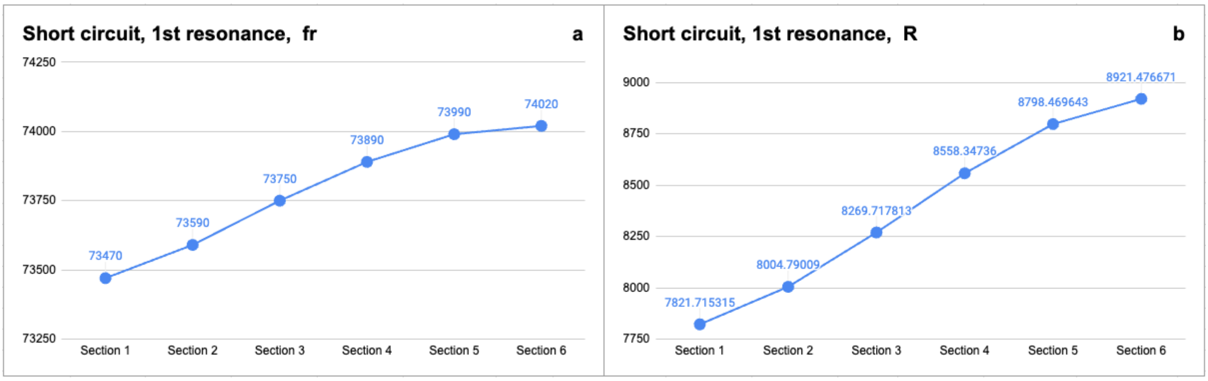

Fig. 9. The FR results in SC mode: a) – resonant frequency; b) – input impedance when one of the links has a resistance relative to the case of 0.2 MΩ

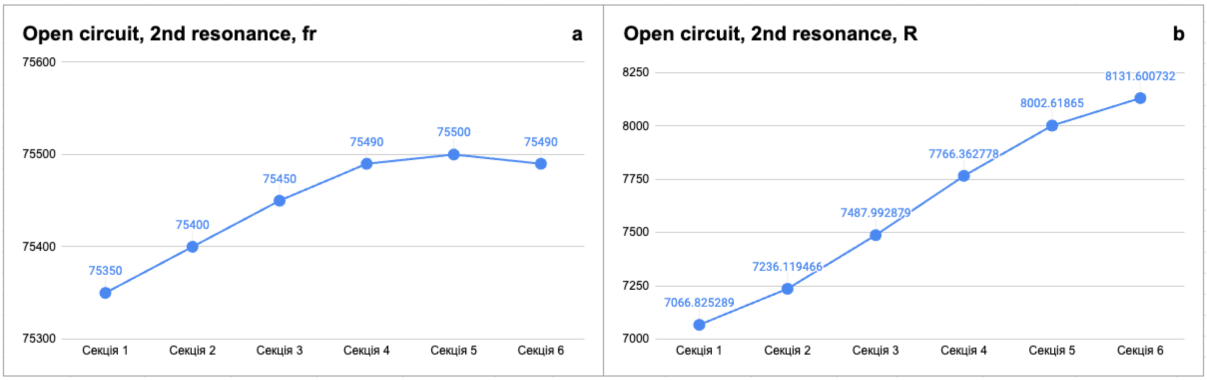

Fig. 10. The FR results in OC mode: a) – resonant frequency; b) – input impedance when one of the links has a resistance relative to the case of 0.2 MΩ

In the presence of a defect of 0.2 MΩ, the character of the resistance distribution also has an almost linear increasing character (Fig. 9, b). The percentage difference in the resistance of the first and sixth winding coils for the SC scheme (Fig. 9, b) is 14.06% and 15.07% for the OC scheme (Fig. 10, b). The relative difference in the resonant frequency of the first and sixth sections for the SC scheme (Fig. 9, a) is 0.75% and 0.19% for the OC scheme (Fig. 10, a).

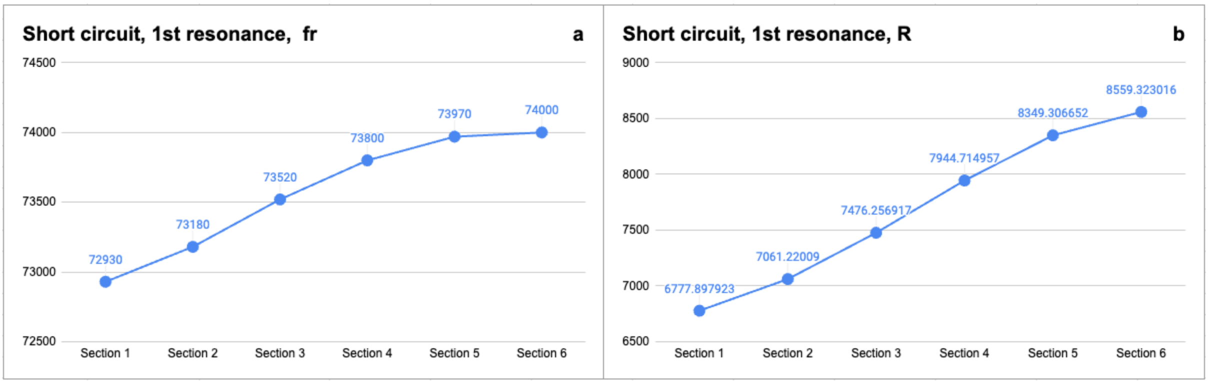

Fig. 11. The FR results in SC mode: a) – resonant frequency; b) – input impedance when one of the links has a resistance relative to the case of 0.1 MΩ

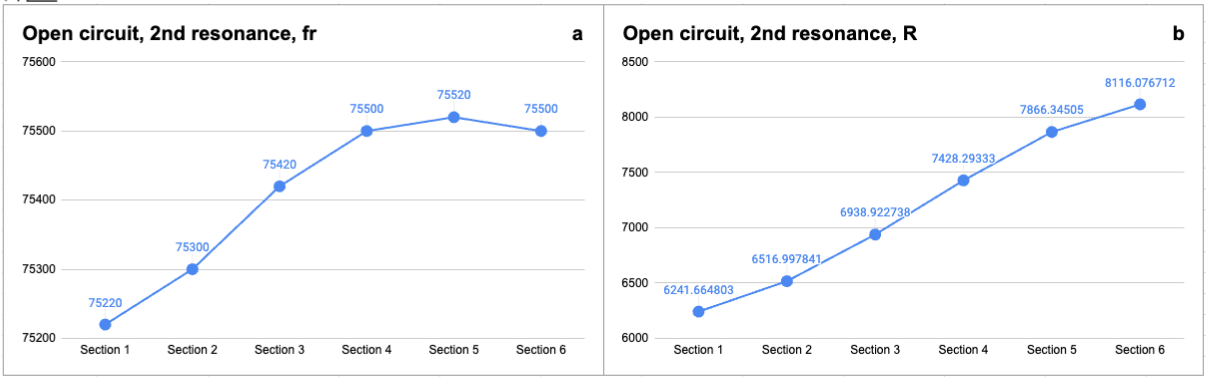

Fig. 12. The FR results in OC mode: a) – resonant frequency; b) – input impedance when one of the links has a resistance relative to the case of 0.1 MΩ

At a defect of 0.1 MΩ, the character of the resistance distribution remains almost linearly increasing (Fig. 11, b). The percentage difference in the resistance of the first and sixth winding coils for the SC scheme is 26.28% (Fig. 11, b) and 30.03% for the OC scheme (Fig. 12, b). The relative difference in the resonant frequency of the first and sixth sections for the CS scheme (Fig. 11, a) is 1.47% and 0.37% for the OC scheme (Fig. 12, a).

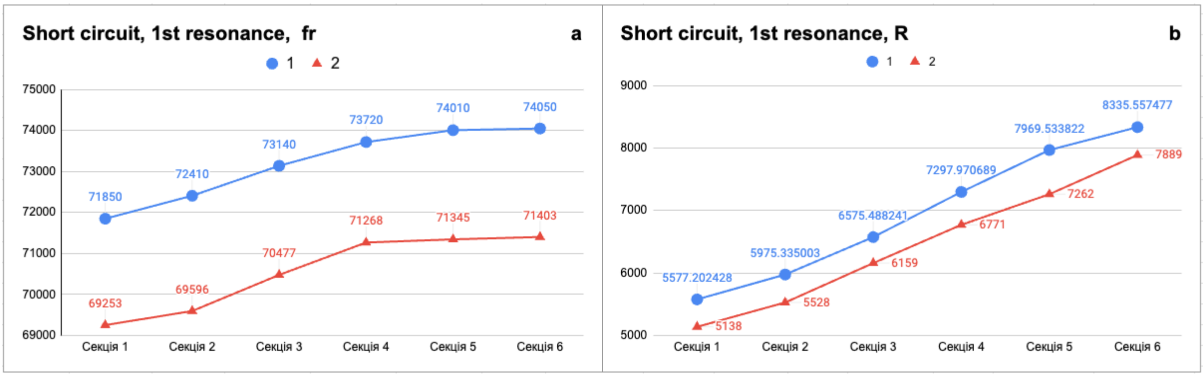

Fig. 13. The FR results in SC mode: a) – resonant frequency; b) – input impedance when one of the links has a resistance relative to the case of 0.05 MΩ, model results (1) and experimental results (2)

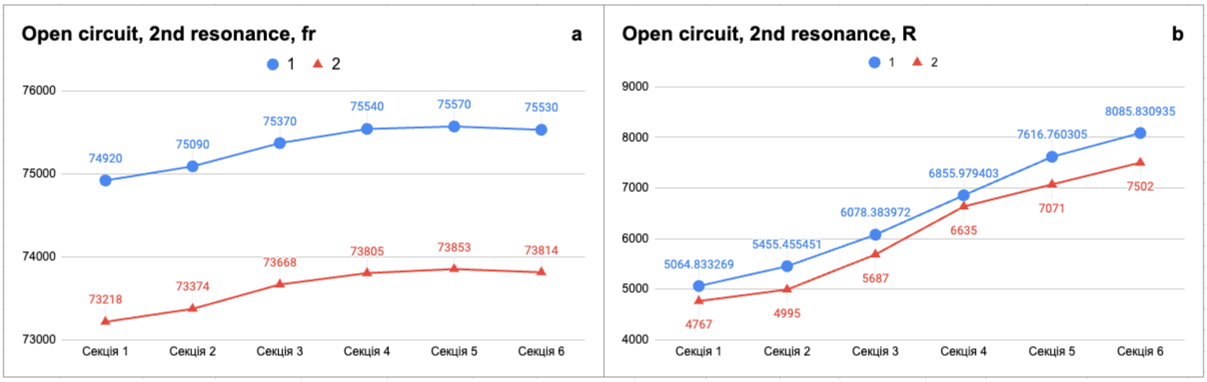

Fig. 14. The FR results in OC mode: a) – resonant frequency; b) – input impedance when one of the links has a resistance relative to the case of 0.05 MΩ, model results (1) and experimental results (2)

Similarly, with a defect of 0.05 MΩ, the nature of the resistance distribution remains almost linearly increasing (Fig. 13, b). The percentage difference in the resistance of the first and sixth winding coils for the SC scheme (Fig. 13, b) is 49.46% and 59.65% for the OC scheme (Fig. 14, b). The relative difference in the resonant frequency of the first and sixth sections for the SC scheme (Fig. 13, a) is 3.06% and 0.81% for the OC scheme (Fig. 14, a).

The FR analysis shows that at zero frequency, the input impedance of the presented multilink circuit turns into a degenerate multilink quadrupole where, in fact, there are no capacitances with infinite resistance, and the inductance turns into an active resistance corresponding to the phase resistance. Also, the longitudinal two-pole with a resistance equivalent to eddy current losses disappears. In fact, the input impedance is the total impedance of the parallel branches and, if the parameters of the links are equal, it is the same for all phases. In the presence of a defect in any part of the winding, the input impedance at zero frequency will be predominantly determined by the resistance of the defective link, depending on the severity of the defect, and corresponds to a decrease in this resistance (Fig. 6). At zero frequency, only the presence of a defective phase can be detected, but it is impossible to determine the location of the defect.

The method of detecting the defect and its location is as follows. The defective phase is determined by measuring the resistances at zero frequency. The resistances of three phases are measured, of which two are considered faultless. We determine the ratio of the resistance of the defective and faultless phases. The lower this ratio is, the more developed the phase defect is and the closer the state of the machine's insulating structure is to the emergency condition. According to the standards, the insulation resistance of the winding in relation to the body should not be less than 0.5 MΩ – this is the boundary value between a defect-free and a defective state. We assume a reference value of the phase resistance R_S in relation to the body of 1 MΩ, which is twice the limit value. Therefore, the defect rate line will look like this – defect rate $K_d = \frac{R}{R_S}$. If K_d greater than or equal to 1, the phase is defect-free. 0.5 – the threshold value from which the defect level determination begins. 0.2 is first-degree defect, 0.1 is a second-degree defect, 0.05 is a third-degree defect, and less than that is an emergency condition.

To analyze the condition of the ground-wall insulation, first, the symmetrical three-phase winding is alternately connected to a signal generator with a range of up to 0 to 1 MHz. With the Hioki IM3570, the measurement method is greatly simplified. Then, alternately, for each phase, the FR and PR are taken in two modes – mode OC, that is, with the free end of the phase and in SC mode, with the neutral shorted to the body and ground.

After comparing the recorded data in all three phases, provided that all phases are equal, the case insulation is considered defect-free. If the resistance is lower in any of the phases, this indicates a defect in the insulation in that phase. Other types of insulation: inter-turn, inter-coil and inter-phase insulation are tested separately, using other methods.

As for the location of the defect in the winding, the local defect is determined at the level of the phase coil number. In the example of the motor under study, the phase has 6 coils. The value of the defect on the direct current can be measured with an ordinary megohmmeter. If a ground-wall insulation defect is not detected by conventional methods in DC testing, but frequency methods reveal a significant difference in resonant impedances and frequencies between phases when the phases are permuted in a circular pattern, this indicates a longitudinal insulation defect. The method of detecting longitudinal insulation defects is the subject of separate studies. In the case when the input impedance is 37.6% less than the input resonant impedance of the defect-free phase, this corresponds to a defect of 0.05 MΩ and below, which is a pre-emergency state. The highest ratio of input impedances corresponds to the location of the defect in the first coil of the phase. Then the ratio decreases linearly to 6.76%, which corresponds to the location of the defect in the last coil. We reconnect the motor leads, i.e., connecting to a high-frequency power supply, we swap the beginning and end of the winding. If the results are the opposite, i.e. the input resistance is very close to the defect-free state and differs by about 6.76%, then the defect is located in the first coil. If, on the contrary, the resistance is initially close to the defect-free state, and after reconnection, it differs by about 37.6% or more from the defect-free value, then the defect is in the sixth coil. If the measured resistance is initially 33.16% less, and after reconnection it's less by 10.85%, then the defect is in the second coil, if vice versa - first 10.85%, and then 33.16% - then in the fifth. If the resistance is initially 26.45% less, and after reconnection it is 19% less, then the defect is in the third coil, and vice versa, in the fourth. When diagnosing, the values of deviations may differ from those described above, so the data provided should be taken more as a guideline, and not as universal values for all cases.

If the defect is 0.1 MΩ on direct current in OS mode, then having a deviation of 24% before reconnection and 4.25% after, it can be argued that the defect is in the first coil, if the deviation value is mirrored, the defect is in the sixth coil. If the resistance is 21% lower before reconnection and 6.6% lower after, the defect is in the second coil, and vice versa - in the fifth coil. If the resistance is 16.36% less and 11.13% less after reconnection, the defect is in the third coil, and vice versa, in the fourth coil. If the measured DC resistance in OS mode, and, accordingly, the defect itself, is 0.2 MΩ, and the resistance deviation is 12.5% and 0.2% before and after reconnection, respectively, then the defect is in the first coil, and if the situation is mirrored, then in the sixth coil. If the deviations are 10.45% and 1.57%, the defect is in the second coil, and vice versa - in the fifth. And if the deviations are 7.49% and 4.26%, the defect is in the third coil, or in the fourth, if the deviations are mirrored.

If the same diagnostic signs are obtained when reconnecting the phase ends, provided that the DC resistance is below 0.2 MΩ, the defect is integral, i.e., distributed throughout the winding length. Such a defect can be eliminated by means of preventive maintenance procedures in the form of drying and impregnation.

This method is of practical interest to specialists of repair enterprises who have winding data. For EM windings with a different number of coils, the determination of the defective coil number depends on the specific proportion of the input resistance ratio when the start and end are reconnected. E.g. for the case of an eight-coil winding and keeping the integral parameters of a six-coil winding, the deviation of the resistance value from the fault-free phase is approximately 50%, and for 4 coils it is approximately 25%. This range is sufficient to confidently determine the location of the defect coil for almost all general-purpose motors.

For multi-coil sections, it is possible to practice connecting two phases in series, one defective and one faulty, and then reconnecting the start and end of the leads to clarify the number of the defective coil.

5. Conclusions

When the defect is located in the end parts of the winding, the sensitivity of the circuit to detect a defect of the same degree of development is significantly reduced. But this makes it possible, when the circuit is reconnected, for example, into a star, to get the location of the defect that was at the end of the winding at the beginning. Thus, it is possible to determine the location of the defect when comparing diagnostic parameters at the level of winding sections. At the same time, the ratio of diagnostic features, i.e., the extremes of the input resistance and resonant frequencies, makes it possible to increase the sensitivity of the future measuring circuit by connecting two phases, defective and faultless, in series, followed by reconnecting the beginning and end of the leads.

The simulation results indicate that the highest sensitivity to detecting defects in the ground-wall insulation of the windings is observed when using the test circuit in the short-circuit mode and ranges in relative units from 1.07% to 6.76%, depending on the location of the defect, with a resistance to the body of 0.5 MΩ. Taking into account that according to the regulatory documents, the insulation resistance relative to the body for low-voltage general-purpose EM should be at least 0.5 MΩ, the obtained sensitivity is sufficient with a certain residual margin. The degree of development of such defects is an essential diagnostic feature that allows you to make a decision on the further operation of the machine.

In general, a decrease in the defect resistance necessarily leads to a decrease in the input impedance and a shift in the resonant frequency, but the degree of response of the frequency response depends on the location of the defect.

The second diagnostic indicator is the shift of the resonant frequency of the frequency characteristics' extremes. However, this indicator is inferior to the measurement of active resistance in terms of sensitivity and a certain nonlinearity of the displacement of the defect along the winding length.

The set goal can be considered achieved - diagnostic features were identified using frequency diagnostic methods and a methodology for assessing the severity of defects was proposed. The proposed methodology makes it possible to determine whether there are defects in the ground-wall insulation. If there are such defects, the methodology answers whether it is a local or integral defect. If it is a local defect, it allows to determine the location of the defect at the coil level. The proposed method can also partially indicate whether there is a defect in the longitudinal insulation.

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ВИСОКОЧАСТОТНІ ПРОЦЕСИ В ОБМОТКАХ ЕЛЕКТРИЧНИХ МАШИН ЗАГАЛЬНОГО ПРИЗНАЧЕННЯ ПРИ НАЯВНОСТІ ДЕФЕКТІВ КОРПУСНОЇ ІЗОЛЯЦІЇ

Дефекти ізоляції в цілому, зокрема проблеми корпусної ізоляції, є одними з головних причин виходу з ладу асинхронних двигунів загального призначення. Більшість статей на цю тему фокусуються на більш складних, вартісних і всебічних методах діагностики, але вони не завжди доцільні та виправдані для електричних машин малої та середньої потужності, які широко використовуються в аграрному секторі. У даній статті розглядається актуальна проблема діагностики корпусної ізоляції. А саме розробка такої методики діагностики, яка б не була ресурсозатратною, не вимагала б складного обладнання і була проста у застосуванні.

Перевірено, що використання одноланкової схеми заміщення для високочастотних досліджень може вказати на наявність дефекту корпусної ізоляції в конкретній фазі обмотки, але не може бути використана для більш детального аналізу, наприклад, щоб знайти місце дефекту.

Показано, що при використанні багатоланкової схеми заміщення можливо моделювати пошкодження корпусної ізоляції обмоток при розташуванні дефектів різного ступеню розвиненості по всій довжині обмотки на рівні однієї котушки. Проведено високочастотні випробування в цій математичній моделі і зібрано дані, а саме резонансну частоту та вхідний опір при резонансі, для дефектів різних ступенів у різних місцях обмотки в режимах з вільним та заземленим кінцем. Паралельно з математичним моделюванням було проведено розрахунки резонансної частоти по інженерним формулам для контролю результатів математичної моделі.

Також було проведено ряд експериментальних досліджень, на спеціально підготовленому зразку реального двигуна 4A90L2, для перевірки збіжності результатів математичного моделювання з реальними дослідними даними. Експериментальні дані підтверджують адекватність моделі, а результати відрізняються не більше ніж на 5-7%, що вказує на достатню точність математичної моделі.

Як результат, запропоновано конкретний алгоритм реалізації методу виявлення дефектів корпусної ізоляції багатовиткових низьковольтних електричних машин загального призначення за допомогою високочастотних впливів, шляхом аналізу вхідного опору та резонансної частоти при порівнянні дефектних та бездефектних фаз у симетричних трифазних обмотках. Запропонований метод дає можливість визначити наявність локального або інтегрального дефекту корпусної ізоляції. У випадку локального дефекту, він дає можливість визначити місце дефекта до рівня котушки обмотки. А також цей метод частково може вказати на наявність дефектів поздовжньої ізоляції.

Ключові слова: *вхідний опір, резонансна частота, амплітудно-частотні та фазо-частотні характеристики, дефекти ізоляції обмоток, багатоланкова схема заміщення.*

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