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Ways of efficiency improvement of local diagnostic of the cores of induction motor stators

Abstract. *Methods for improvement of technical and economic characteristics of the systems of local diagnostics of electric machines laminated cores are considered. Operating conditions of power supplies and diagnostics terms providing its best validity are substantiated. The efficiency of application of the considered method and system of diagnostics for obtaining spatial local distribution of electric and magnetic properties of cores of induction motor stators is confirmed.*

Streszczenie. *W artykule rozpatrzono metody poprawy technicznych i ekonomicznych charakterystyk systemów lokalnej diagnostyki rdzeni maszyn elektrycznych. Wykazano, że najlepszą walidację osiąga się poprzez warunki działania układów zasilających i parametry diagnostyczne. Potwierdzono sprawność rozpatrywanych metod i systemu diagnostycznego dla otrzymania przestrzennego lokalnego rozkładu właściwości elektrycznych i magnetycznych rdzeni stojanów maszyn elektrycznych. (**Sposoby poprawy efektywności lokalnej diagnostyki rdzeni stojanów silników indukcyjnych**)*

Key words: stator core, local diagnostics, validity, induction motor
Słowa kluczowe: rdzeń stojana, lokalna diagnostyka, walidacja, silnik indukcyjny

Introduction

During long-term operation and repairs of induction motors (IM) the properties of inter-lamina insulation of stator laminated cores change [1]. It is the cause of occurrence of local shorted circuits distributed along the length and in the volume of the cores at random. In this case the properties of the teeth zone change more significantly and irregularly than the properties of the yoke, especially, it concerns the upper part of the teeth. It results in redistribution of the temperature of the stator winding and appearance of local zones of overheats. In contrast to the IM with laminated stator this problem does not arise in the case of electric machines with ironless stator [2, 3]. Also, due to occurrence of spatial magnetic asymmetry, IM vibration parameters deteriorate [4, 5]. To estimate these processes quantitatively it is necessary to have an exact pattern of distribution of electrical and magnetic properties of stator cores. The efficiency of the use of local methods of diagnostics is substantiated for the solution of the mentioned problem [1]. However, the basic method of such diagnostics is characterized by a number of drawbacks decreasing the efficiency of its use.

The purpose of the paper consists in substantiation of the methods for improvement of the efficiency of the developed industrial systems of local diagnostics of IM stator cores.

Theory

The method of local diagnostics of IM stator cores is explained in Figs. 1-2.

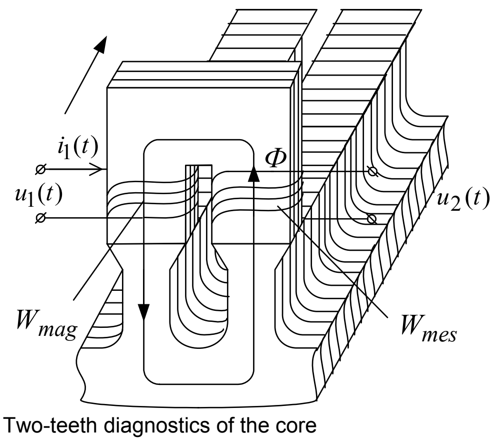

Fig. 1. Two-teeth diagnostics of the core

It allows determination of electrical and magnetic properties of the stator teeth steel for the magnetic induction value equal to its value at varying reversal magnetization of the teeth in a working machine. Steel properties are determined by means of U-type inductors with uniformly applied magnetizing W_{mag} and measuring W_{mes} windings. Inductor in Fig. 1, moving parallel across two teeth of the core, induces the necessary value of magnetic flux Φ in them and in the adjacent part of the yoke. Inductor in Fig. 2 makes it possible to additionally determine the exact location and type of damage of the upper parts of the core teeth.

During the research the main faults of the basic method of local diagnostics were singled out and methods for their compensation were proposed. The results of this research are shown in Table 1.

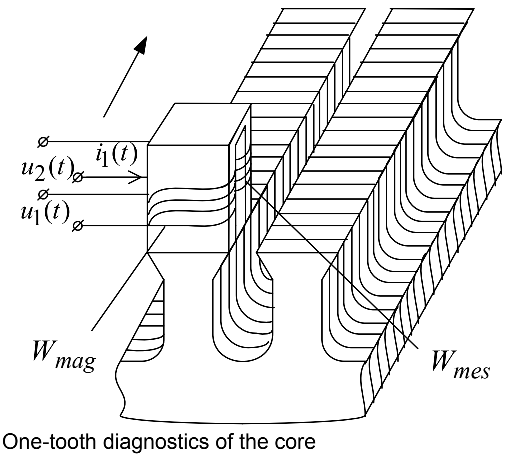

Fig. 2. One-tooth diagnostics of the core

It can be seen in Table 1 that the first drawback of the basic variant of the system is connected with the necessity to take into account the real character of reversal magnetization in a running motor. It can be solved as a result of a comparative experimental estimation of different methods of reversal magnetization.

Then, three items of Table 1 ground the necessity for development of an adjustable computer-aided power supply with functions of stabilization of the value and harmonic composition of the consumed current.

This problem was solved due to development of a free-form impulse generator built on the basis of a single-phase frequency converter with current feedback, operating according to the "current-mirror" principle. In this case the required amplitude, form and frequency of voltage can be assigned at the output of a digital-analog converter (DAC) of an industrial input-output module supporting analog-output synchronization.

The following problem consists in obtaining a sufficient number of independent (not connected by linear relations) diagnostic parameters. As it was shown in [1], their number can be significantly increased when inductors magnetic system is saturated.

Table 1. Drawbacks of the basic method for local diagnostics and methods for their compensation

Drawback	Compensation method
During two-teeth testing the rotational character of reversal magnetization of the yoke of the working IM stator is not taken into account.	To determine the real value of steel losses in IM stator, during local two-teeth testing, it is necessary to provide a stator core yoke magnetic flux equivalent to the flux from rotational reversal magnetization in a working machine at the required value of magnetic flux of the varying reversal magnetization of the teeth.
One-tooth local testing at a commercial frequency does not allow determination and size of short-circuited areas distributed along the height of the tooth.	To determine the real state of the tooth zone and location and size of short-circuited sections during one-tooth testing of the core it is necessary to use an independent source of sinusoidal voltage with varied amplitude and frequency. It will allow the change of the depth of magnetic flux penetration into the tooth zone of the core.
Reliability of one-tooth local diagnostics sharply reduces when harmonic composition of supply voltage changes.	During local diagnostics it is necessary to use an independent source of sinusoidal voltage with a possibility of stabilization of harmonic composition of supply voltage when the value and character of the load change.
A part of diagnostics parameters prove to be spurious as the error of their measurement exceeds the interval of their variation with the basic types of cores defects.	To increase the number of diagnostic parameters it is necessary to adapt the existing mathematical software to the conditions of operation of the diagnostics system, using improved methods of determination of parameters applying methods of digital smoothing and filtration of the measured signals.
Local diagnostics in a manual or an automated mode is rather a labor-consuming procedure as the necessary pitch of inductors shift, at which it is most informative, is 2-3 mm.	To provide the highest efficiency of the use the system of local diagnostics is to be completely automated taking into consideration the real state of the diagnosed cores.

In this case effective values of voltages U_1, U_2 and current I_1 are not connected unambiguously by definite numerical relations with their mean and amplitude values, and angles of phases shift between curves $u_1(t)$, $u_2(t)$ and $i_1(t)$ do not have clear physical interpretation, in fact.

I.e. it is possible to separately analyze parameters for every harmonic and, besides, a number of integral parameters that characterize the signal on the whole. The latter mostly do not have physical interpretation but they are sensitive to diagnosed damages of cores.

Under these conditions diagnostic parameters are to include, first of all, the ones characterizing the basic electric and magnetic properties of the inductor – core section circuit. In the first place, they are magnetic field strength H, magnetic induction B_m, coefficients of harmonics of curves of magnetization current THD_{I1} and voltage THD_{U2} at the test coil, circuit magnetic impedance Z_m and steel losses P_μ. Also, informative parameters may include an angle of phases shift between the curves of magnetization current and voltage at the test coil φ_{I1U2}, resistance $R_{\mu 1}$ and reactance $X_{\mu 1}$ of magnetization circuit at the first harmonic, amplitudes of instantaneous power components [1].

When digital measurement devices are used, the analyzed parameters are calculated on the basis of the following relations.

1. Magnetic field strength

(1) $$H = \frac{I_1 W_{mag}}{l_m},$$

where I_1 – effective value of magnetization circuit current calculated on the basis of relation

(2) $$I_1 = \sqrt{\sum_p I_{1p}^2 + I_{10}^2}.$$

Here p – number of analyzed harmonics in the signal $i_1(t)$; I_{1p} – effective values of corresponding harmonics of the signal

(3) $$I_{1p} = \sqrt{\frac{1}{T}\int_0^T \left(I_{1p\,max}\,sin\left(p\omega t + \varphi_p\right)\right)^2 dt},$$

where $I_{1p\max}, \varphi_p$ – respectively the amplitude and the initial phase of harmonic components obtained from Fourier expansion; I_0 –value of current constant component

(4) $$I_{10} = \frac{1}{N}\sum_{n=0}^{N-1} I_{1n}.$$

In (4) N – number of discretization points in the period; l_m – length of a mean line for magnetic flux in inductor – core section circuit;

2. Magnetic induction

(5) $$B_m = \frac{U_{2m}}{4 f W_{mes} S},$$

where U_{2m} – mean value of test coil voltage calculated by relation of (4) form for U_{2n}; f – frequency of power voltage change; S – sectional area of inductor bar;

3. Coefficients of harmonics of magnetization current and voltage curves at test coil

(6) $$THD_x = \frac{\sqrt{\frac{1}{m}\sum_{q=0}^{m-1}\left(x\left(t_q\right) - X_{1max}\,sin\left(\omega t_q + \varphi_1\right)\right)^2}}{X_1},$$

where $x(t_q)$ – instantaneous values of the analyzed signal at discretization points t_q; X_{1max} and φ_1 – amplitude and initial phase of the first harmonic of the signal ;

4. Magnetic impedance of the inductor and the researched section of the package

(7) $$Z_m = \frac{I_1 W_{mag}}{B_m S}.$$

(8)

5. Steel losses

(9) $$P_{\mu} = \sum_{p} P_{\mu\, p} ,$$

where

(10) $$P_{\mu\, p} = \frac{W_{mag}}{W_{mes}} \frac{a_{i1p} a_{u2p} + b_{i1p} b_{u2p}}{4} ,$$

$a_{u2p}, b_{u2p}, a_{i1p}, b_{i1p}$ – quadrature components of harmonics of voltage $u_2(t)$ and current $i_1(t)$, obtained as a result of Fourier expansion;

6. Resistance and reactance of magnetization circuit at the first harmonic

(10) $$R_{\mu 1} = Re\left(\frac{U_{21} e^{j\varphi_{u21}}}{I_{11} e^{j\varphi_{i11}}} \right);$$

(11) $$X_{\mu 1} = Im\left(\frac{U_{21} e^{j\varphi_{u21}}}{I_{11} e^{j\varphi_{i11}}} \right),$$

where U_{21}, I_{11} and $\varphi_{U21}, \varphi_{I11}$ – respectively effective values and phases of the first harmonics of voltage $u_2(t)$ and current $i_1(t)$, $Re(...), Im(...)$ – real and imaginary parts of complex impedance.

To improve the measurement accuracy the phases shift angle φ_{I1U2} is to be determined by reconstruction of actual crossing the time axis by curves $u_2(t)$ and $i_1(t)$.

The obtained results enabled development of an experimental model of an automated system for stator core local diagnostics. The general view of the model is shown in Fig. 3. The external view of the actuator with installed inductors is shown in Fig. 4.

Fig. 3. General view of an industrial model of an automated system of local diagnostics of stator cores

A personal computer equipped with an input-output module E14-440 (manufactured by LCard), necessary sensors and power converters presents the main measure-control body of the diagnostics system.

Experimental research

To perform a comparative estimation of an alternating and rotational reversal magnetization a test coil was applied to a general purpose IM yoke and magnetic induction was controlled by measuring the form and the value of voltage at this coil (induction in yoke) and at the test coil of the inductor (induction in the teeth).

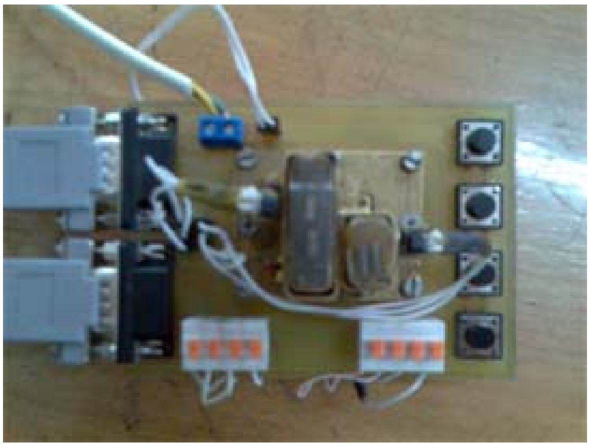

Fig. 4. External view of the actuator of the system of local diagnostics

Results of research with magnetization from IM stator own three-phase winding and inductor magnetization are shown in Figs. 5, 6.

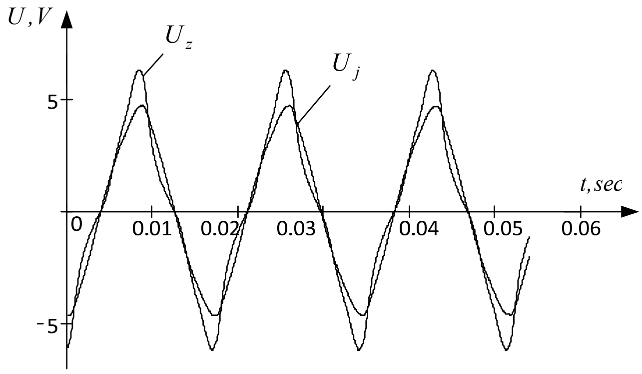

Fig. 5. Voltage form at test coils of inductor U_z and yoke U_j when stator winding is magnetized

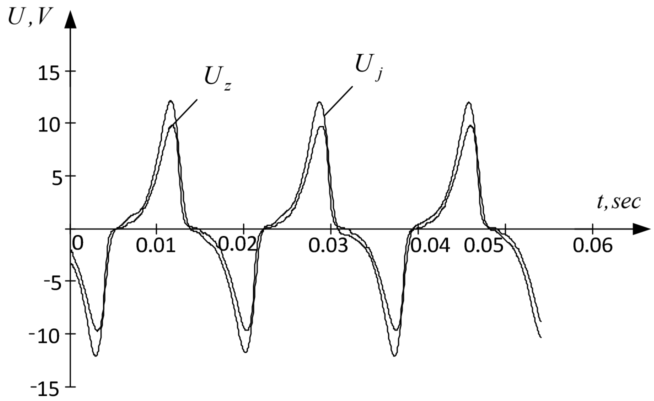

Fig. 6. Voltage form at test coils of inductor U_z and yoke U_j when magnetization is caused by inductor

It is seen in Fig. 5 that the form of voltage in the winding applied to the yoke is practically sinusoidal and in teeth it is nonsinusoidal. However, it should be noted that when this method of magnetization is used, proportionality B_{mz} / B_{mj} between the values of magnetic induction in the teeth and the yoke is violated.

On the contrary, when local testing is carried out in the usual way, the form of the curve at the magnetizing winding of the yoke is nonsinusoidal and contains all the odd harmonics, up to15 inclusive, which should not occur in a normally running IM.

However, relation B_{mz} / B_{mj} is practically invariable in this case and approaches the relation of the areas of tested sections of the yoke and teeth. Taking into account identity of harmonic composition of magnetic induction in the teeth and the yoke and equal phase shift of corresponding curves (Fig. 6), it provides the possibility to easily exclude steel losses in the yoke from the results of testing. With this purpose in view, value of section-mean induction determined from IM structural parameters is used

To determine efficiency of modifying the degree of saturation of magnetic circuit and the frequency of supply voltage, basic types of core damages were created artificially. In this case the analyzed parameters were first determined for undamaged sections of IM cores and then the same sections were forcibly short-circuited or loosened. Results of research for separate parameters are shown in Figs. 7, 8. On the whole they confirm the possibility of determination of optimum values of inductor supply voltage and its frequency.

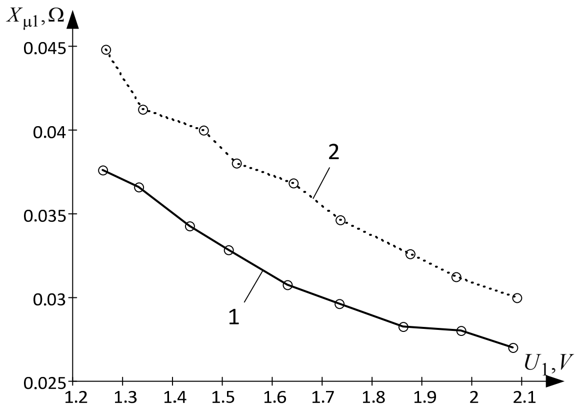

Fig. 7. Character of dependences $X_{\mu 1} = f(U_1)$, when voltage is modified (1 – undamaged section, 2 –short-circuited section)

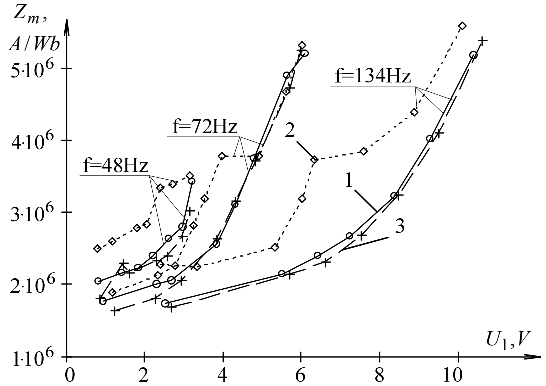

Fig. 8. Character of dependences $Z_m = f(U_1)$ when frequency is modified (1 – undamaged section, 2 –short-circuited section, 3 – loosened section)

Besides, the possibility of additional improvement of validity of local diagnostics, when irregularity of air gap in the zone of the core and inductor contact is compensated, was confirmed during the research. It is proved that it can be attained by transition to contactless diagnostics with optimum air gap width at which informative value of diagnostic parameters is not lost.

Besides, the efficiency of the considered diagnostics method for obtaining spatial local distribution of electric and magnetic properties of the cores of IM stators contained in a diagnostic system was confirmed (Fig. 9).

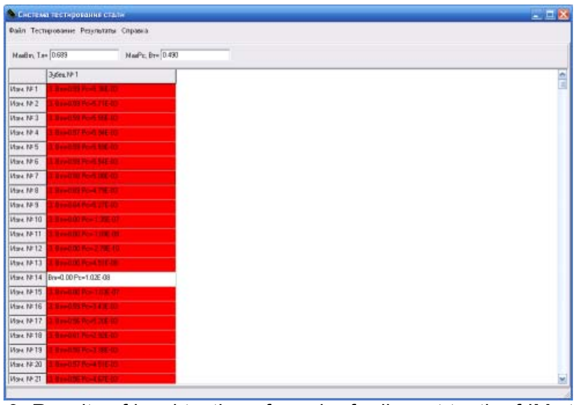

Fig. 9. Results of local testing of a pair of adjacent teeth of IM stator core (damaged teeth are marked with color)

Conclusions

1. Ways of improvement of reliability and efficiency of the method of local diagnostics of laminated cores have been substantiated. These ways make it possible to compensate for basic drawbacks of the main method and present the grounds for the developed industrial systems of local diagnostics of IM stator cores.

2. Optimum values of inductors supply voltage and its frequency as well as distances from the inductor to the diagnosed surface of the core, which provide the highest reliability of local diagnostics, have been theoretically substantiated.

3. The efficiency of application of the developed method and system of diagnostics for obtaining spatial local distribution of electrical and magnetic properties of IM stator cores has been confirmed.

REFERENCES

[1] Prus V.V., Zagirnyak M.V., Nikitina A.V., Grounds for Efficiency and Prospect of the Use of Instantaneous Power Components in Electric Systems Diagnostics, *Przeglad Elektrotechniczny (Electrical Review)*, No 12 (2006), pp. 123 – 125.

[2] Virtic P., Variations of Permanent Magnets Dimensions in Axial Flux Permanent Magnet Synchronous Machine, *Przeglad Elektrotechniczny (Electrical Review)*, 87 (2011), No. 12B, 194-197.

[3] Virtic P., Avsec J., Analysis of coreless stator axial flux permanent magnet synchronous generator characteristics by using equivalent circuit, *Przeglad Elektrotechniczny (Electrical Review)*, 87 (2011), 208-211.

[4] Hadziselimovec M., Marcic T., Stumberger B., Zagradicnik I., Winding type influence on efficiency of an induction motor, *Przeglad Elektrotechniczny (Electrical Review)*, 87 (2011), No 3, pp. 61 – 64.

[5] Macus D., Drobnic K., Ambrozic V., Miljavec D., Fiser R., Nemec M., Parameters estimation of induction motor with faulty rotor, *Przeglad Elektrotechniczny (Electrical Review)*, No 1a (2012), pp. 41 – 46.

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