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Taking stator cores properties into account when induction motors vibration parameters are calculated

Abstract. *Problems of induction motor stator core condition influence on the general pattern of magnetic field distribution, magnetic tension tensor space distribution and the value of electromagnetic vibroexcitating force are researched. The necessity of taking into account different changes of properties of steel of yoke and teeth zone, as well as nonuniform distribution of stator core teeth zone properties, when vibration electromagnetic component is calculate, is substantiated.*

Streszczenie. *Badano wpływ rozkładu pola magnetycznego I wibracji na warunki pracy twornika silnika indukcyjnego. W szczególności uwzględniono zmianę właściwości stali rdzenia. (Badanie właściwości materiału twornika przy projektowaniu silnika indukcyjnego z uwzględnieniem wibracji)*

Key words: induction motor, stator core, vibration electromagnetic component, magnetic properties.
Słowa kluczowe: silnik indukcyjny, wibracje, właściwości materiału magnetycznego

Introduction

During long-term induction motor (IM) usage, alternating with a number of repairs, the properties of stator laminated core interlamination insulation change [1]. It results in occurrence of local shorted circuits randomly distributed along the length and across the volume of the core. The mentioned phenomenon causes winding overheating at local sections and increased vibration of the electric machine (EM). Neglect of taking into account the change and irregularities in distribution of stator core properties prevents one from correct estimation of admissible EM operating conditions. The consequence of this is their quicker failures due to stator winding overheating and vibration. There are a number of efficient calculation methods to determine thermal condition of such IM. At the same time the problem of estimation of the magnetic system properties change influence on IM vibration parameters remains uninvestigated.

Problem statement

The purpose of the paper consisted in substantiation of the promising method of IM vibration parameters research when the properties of its magnetic system change.

Background

According to the results of local analysis of IM stator core material properties, they change unevenly along the length and across the volume of the cores [1]. Taking into consideration the fact that stator cores yokes are not subjected to such intensive mechanical and thermal effects as their teeth, yoke steel properties variation may not be as significant [1]. For relative quantitative estimation of changing properties of steel of yoke and teeth zone the authors researched the properties of stator core of 4A series 4A132M2U3 type IM of general industrial application.

This core was subjected to annealing in the air at the temperature of 400^oC during four hours, which corresponds to conditions of winding removal during overhauls. To take into account the influence of teeth mechanical damages, unavoidable during overhauls, the stator initial winding was restored after each annealing. Besides, after every repair of the core, the researched IM was subjected to intensive current and mechanical loads at a test board imitating conditions of its normal operation.

The obtained technical magnetizing curves $B = f(H)$ and losses variation dependences $P_{mag} = f(B)$ are shown in Figs. 1 – 2 (dependences before the overhaul are designated by 1, after the first-third overhauls – by figures 2 – 4, respectively).

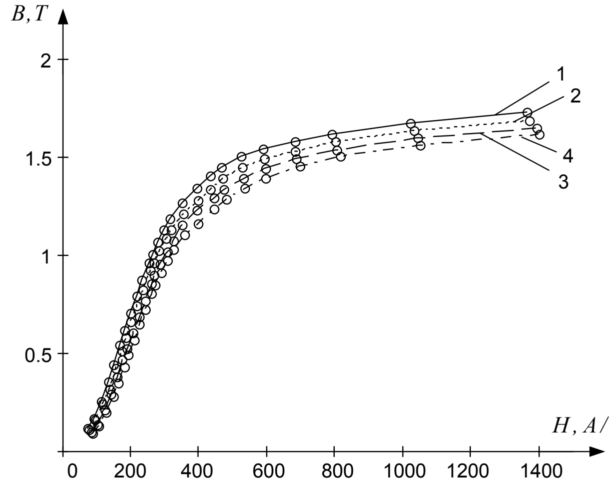

Fig. 1. Technical magnetizing curves of stator core yoke steel of 4A132M2U3 type IM at successive overhauls.

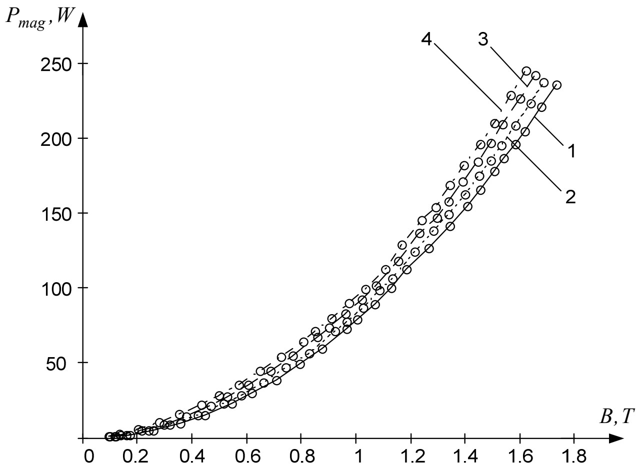

Fig. 2. Curves of stator core steel losses of 4A132M2U3 type IM at successive overhauls

It can be seen in Figs. 1 – 2 that at yoke steel temperature annealing and subsequent removal of stator winding the change of its properties is uniform and not very significant. So, after every subsequent overhaul, magnetic induction decreases only by 2.59; 4.96 and 7.57%, and steel losses grow by 6.21; 12.57 and 18.69%, respectively.

It can be explained by pressure constancy due to larger solidity and rigid fixation of yoke separate sheets (stator core yoke of 4A series IM is fixed by welding joints). I.e. interlamination insulation failure because of mechanical damages during winding removal is practically excluded.

On the other hand, the change in tooth zone steel properties is more considerable, which can be explained by additional mechanical effects during the process of winding removal [1].

The results of steel properties variation, obtained with the use of local test method [1] for a section of yoke and 10 mm long tooth zone, which corresponds to the linear dimension of the measuring inductor, are shown in Figs. 3-4. In Fig. 3: 1 – losses dependences before the overhaul; 2-4 – after 1-3 overhauls; in Fig. 4: 1 – losses dependence for a normal section. 2 – the same after forced shorting of steel sheets in the upper part of tested teeth, which imitates their mechanical damage, 3-5 – losses dependences after 1-3 overhauls.

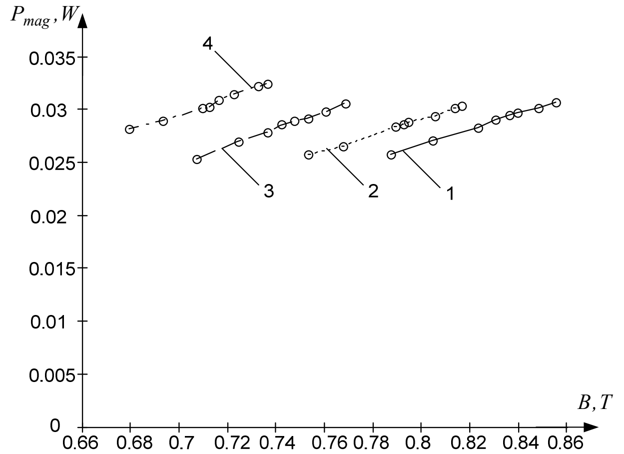

Fig. 3. Curves of steel losses variation at the stator core section of 4A132M2U3 type IM at successive overhauls

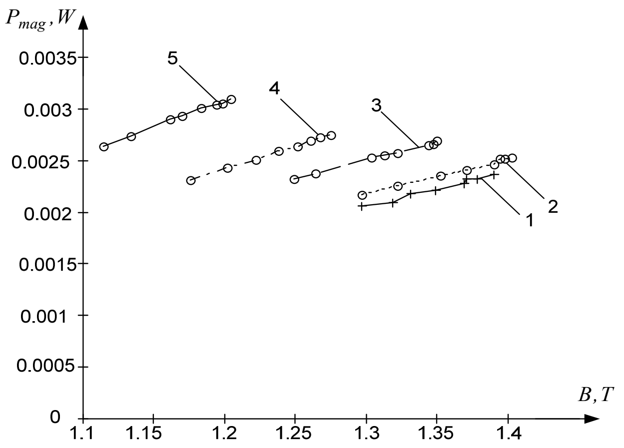

Fig. 4. Curves of steel losses variation in the teeth zone section of 4A132M2U3 type IM after its forced shortening and successive overhauls

It can be seen in Figs. 3-4 and proved by the results of the experiment that yoke section steel properties changes correspond to the change of steel properties in the whole yoke and growth of losses at the tooth zone researched section is 5,48; 21; 38,2; 74,82%, respectively, which significantly exceeds losses growth in the yoke.

Besides, local testing data point out significant irregularity of magnetic induction distribution along the core length in relation to its value at the undamaged section B_{norm}. So, for Fig. 5 showing change of magnetic induction along the stator length for mostly damaged teeth of 4A132M2У3 type IM, the minimum induction value is by 30% lower than B_{norm}. It is the evidence of irregularity of the core magnetic properties distribution and may result in nonuniform distribution of the main magnetic flux in operating IM and, consequently, in increase of vibration electromagnetic component.

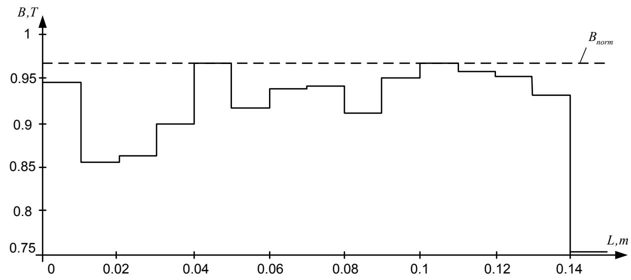

Fig. 5. Magnetic induction variation along the length of mostly damaged teeth of stator core of 4A132M2U3 type IM

Theory

Taking into account a complicated interconnection of stator core properties with IM vibration parameters and impossibility to use magnetic circuit calculation methods in this case, the necessity of solution of this problem in field setting has been substantiated.

To take the described changes of steel properties into account it is necessary to assign yoke and teeth parameters separately and also to model the real pattern of location of core damage zones in the axial and radial direction, which can be obtained using methods of the core local testing according to [1].

In this case the calculation of magnetic field distribution is limited by the surface of the stator core where Dirichlet condition $A_z = 0$ can be assigned for vector magnetic potential component perpendicular to the cross section of the machine in the Cartesian coordinate system.

An important element of further calculation consists in determination of electromagnetic vibroexcitating forces which can be found using Maxwell magnetic tension tensor $\vec{T}$ characterizing the density of electromagnetic force applied to the stator bore surface [2].

Components of magnetic induction vector in Cartesian coordinate system are the basis for calculation of magnetic tension tensor. They are determined according to the formulas

(1) $$\vec{B}_x = \partial \vec{A}_z / \partial y \; ; \; \vec{B}_y = -\partial \vec{A}_z / \partial x \, .$$

Normal $\vec{B}_n$ and tangential $\vec{B}_\tau$ components of magnetic induction vector projection for an arbitrary point with coordinates x, y are determined according to the known projections $\vec{B}_x, \vec{B}_y$ on the internal surface of the stator, obtained from the results of electromagnetic field calculation.

(2) $$\vec{B}_n = 2\left(y\vec{B}_y + x\vec{B}_x\right)/D_s \; ; \; \vec{B}_\tau = 2\left(y\vec{B}_x + x\vec{B}_y\right)/D_s \, ,$$

where D_s – stator internal diameter.

Magnetic tension tensor vector is expressed through its normal T_n and tangential T_τ components

(3) $$\vec{T} = \vec{n}T_n + \vec{\tau}T_\tau .$$

Normal component T_n of magnetic tension tensor characterizes action of radial vibroexciting forces and tangential component T_τ – torque oscillations.

Interconnection of normal and tangential components of magnetic induction vectors $\vec{B}$ and normal component of magnetic tension tensor $\vec{T}$, when their directions do not coincide in space, is determined according to equation [2]:

(4) $$T_n = \left| \frac{1}{2\mu_0}\left(\vec{B}_n^2 - \vec{B}_\tau^2\right) \right| ; \; T_\tau = \left| \frac{\vec{B}_n \vec{B}_\tau}{\mu_0} \right| .$$

Normal and tangential components of tensor $\vec{T}$ with known projections in Cartesian coordinate system are found by the following expressions:

$$T_n = T_y \cos\alpha + T_x \sin\alpha = T_y \frac{2y}{D_s} + T_x \frac{2x}{D_s} ;$$

(5) $$T_\tau = T_x \cos\alpha - T_y \sin\alpha = T_x \frac{2y}{D_s} - T_y \frac{2x}{D_s} .$$

where T_y, T_x – $\vec{T}$ projections on coordinate axes x, y, α – angle between the abscissa axis and tangential component of magnetic tension tensor within one period of variation of functions (3) $0 \le \alpha \le 2\pi/p$, where p – number of IM pole pairs.

Normal and tangential components of electromagnetic vibroexcitating force were determined by integration by area S of the surface embracing the stator.

(6) $$F_n = \frac{1}{2\mu} \int\limits_S \left(B_n^2 - B_\tau^2\right) dS ;$$

(7) $$F_\tau = \frac{1}{2\mu} \int\limits_S \left(B_n B_\tau\right) dS .$$

Experimental results

Taking into consideration the posted field problem particular features allowing its solution in a 2D setting as well as requirements to the extent of calculation specification, it can be carried out in any application package based on finite element method [3–5].

4A132M2U3 type three-phase IM of general industrial purpose (nominal power $P_n = 11 kW$; poles pairs number $2p = 2$) with above stated integral and local stator core properties was adopted as the object of the research. Stator core teeth form and geometry are shown in Fig. 6.

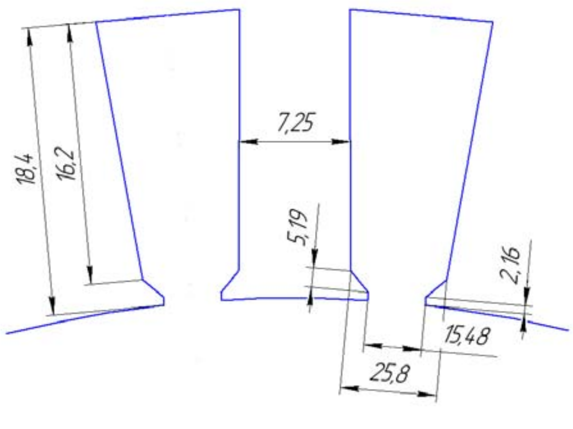

Fig. 6. 4A132M2U3 type IM stator core teeth form and geometry (mm)

All the other design data, parameters of windings, as well as of stator and rotor cores, are taken in accordance with the reference data.

Calculations for three different variants of assignation of stator core properties variation were carried out:

– uniform variation according to averaged magnetizing curves;

– separate taking into account the variations of yoke and teeth zone properties

– additional taking into account the irregularity of teeth zone steel properties distribution.

In the first variant integral variations of steel properties were assigned by the nameplate and real magnetizing curves $B = f(H)$ for the used electric steel of 2013 type (Fig. 1).

In the second variant yoke and teeth properties were assigned separately. Yoke properties were taken into consideration in the same way as in the previous variant. Besides, denticulation with different steel properties was singled out in the lower part of the stator in the developed model (Fig. 7).

Decrease of magnetic induction in the yoke was assumed at the level of 10%, in the teeth – 25%, which corresponds to the third overhaul [1].

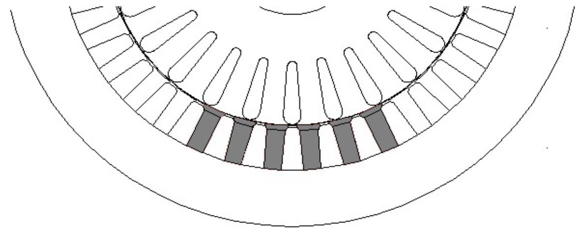

Fig. 7. Concerning explanation of different assignment of yoke and teeth properties in the analyzed model

In the third variant the properties of the upper part of the stator core teeth, as mostly damaged section of IM magnetic system, were additionally assigned (Fig.8).

Decrease of induction in the upper part of the teeth was assigned at the level of 75%, which corresponds to the real change of their properties (Fig.4).

During the process of research the change of magnetic field general pattern was estimated, and also values of normal and tangential components of electromagnetic vibro - exciting force and its complete vector were calculated in accordance with (6)-(7). Normal $\vec{B}_n$ and tangential $\vec{B}_\tau$ components of magnetic induction vector projections, used in the calculations, were determined according to the results of magnetic field calculation.

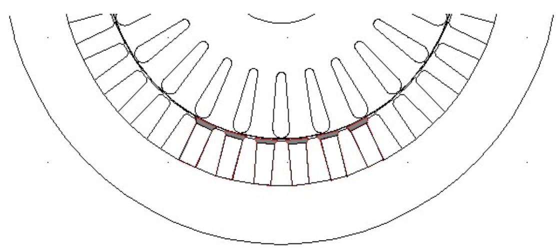

Fig. 8. Separate assignment of steel properties of the teeth upper part

The results of calculation for separate assignment of yoke steel properties in the middle and upper part of the teeth are shown in Figs 9 – 10.

Results of calculation of components and complete vector of electromagnetic vibroexcitating force in the damage zone are presented in Table 1.

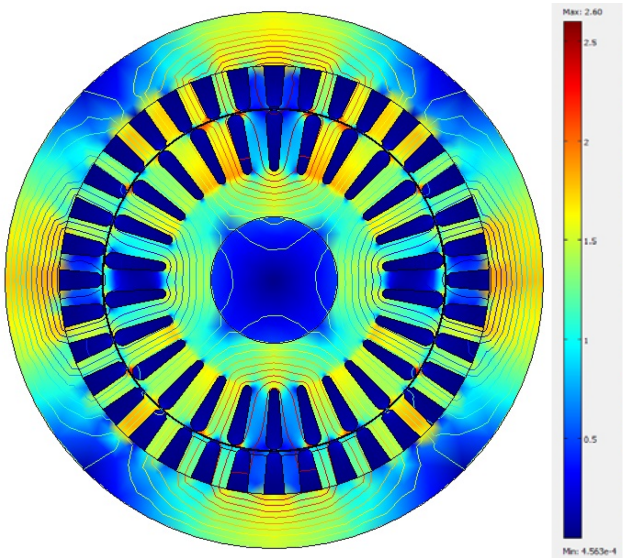

Fig. 9. 4A132M2U3 type IM magnetic field pattern when steel properties of the yoke, middle and upper part of the teeth are assigned separately

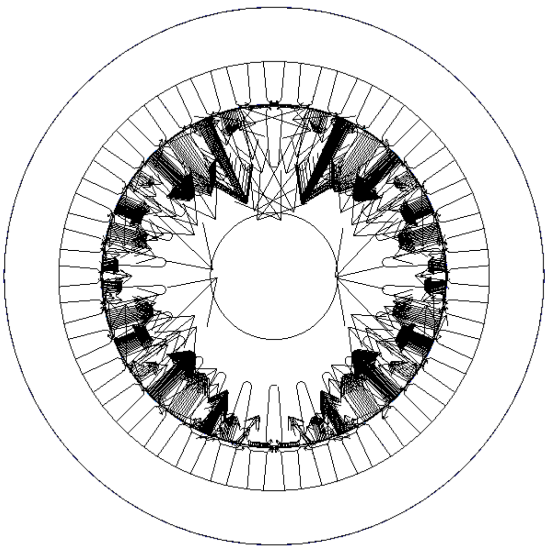

Fig. 10. Distribution of effort tensors three-dimensional vectors for 4A132M2U3 type IM when steel properties of the yoke, middle and upper part of the teeth are assigned separately

Table 1 – Results of calculation of components and complete vector of electromagnetic vibroexcitating force in the damage zone

Components of electromagnetic vibroexcitating force	Undamaged core	Variant 1	Variant 2	Variant 3
F_n, кN	4,961	4,405	3,383	2,221
F_τ, кN	2,522	2,220	1,824	1,429
F, кN	7,016	4,952	3,856	2,655

The calculation results demonstrated that change of teeth zone steel properties considerably weakens IM main magnetic flux. It results in redistribution of electromagnetic efforts in the damage zone.

Data in Table 1 show that separate taking into account the variation of properties of steel of yoke and stator core teeth provides additional decrease of the force by 15.61%.

When irregularity of distribution of the properties of teeth zone steel is taken into account, vibroexcitating force additionally reduces by 17.11%. For normal component F_n these changes are more significant and make 20.61% and 23.42%, respectively.

Taking into consideration the fact that effort components at the diametrically opposite, in relation to the rotor, sections of magnetic circuit consisting of stator teeth – air gap – rotor teeth in a correctly designed machine without faults are balanced, the above described changes result in efforts disbalance, which causes additional vibration.

Thus, the obtained results prove the necessity of taking all the analyzed factors into consideration when estimating IM vibration electromagnetic component.

Conclusions

1. A method for calculating IM magnetic field has been proposed. This method takes into account the real variation of stator core properties and makes it possible to estimate the spatial distribution of magnetic tension tensor and the value of electromagnetic vibroexcitating force.

2. Estimation of the influence on vibroexcitating force components of different variants of assigning stator core properties changes has been carried out. Its results proved the necessity of taking into consideration different changes of yoke steel and teeth zone properties, as well as irregular distribution of the properties of IM stator core teeth zone. The obtained results will be the basis for the following calculations of EM vibration parameters.

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