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ADVANCED RESEARCH OF THE IMPACT OF ROTOR BARS ANISOTROPIC CONDUCTIVITY ON STARTING TORQUE OF AN INDUCTION MOTOR WITH A DIE-CAST COPPER CAGE

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Викладено результати досліджень впливу анізотропії провідності стрижнів ротора на пусковий момент асинхронного двигуна, стендових і експлуатаційних іспитів вибухозахищеного двигуна типу 2ЕКВ3,5-210 потужністю 210 квт із литою анізотропною мідною обмоткою ротора.

Изложены результаты исследований влияния анизотропии проводимости стержней ротора на пусковой момент асинхронного двигателя, стендовых и эксплуатационных испытаний взрывозащищенного двигателя типа 2ЭКВ3,5-210 мощностью 210 кВт с литой анизотропной медной обмоткой ротора.

1. INTRODUCTION

The IM's with the die-cast copper rotors are characterized by the improved efficiency because of the loss reduction as compared with the motors provided with the aluminum rotors [1 – 3]. As for the starting torque, the latter one reduces its value. The above mentioned lack, to a marked extent can be weakened by moulding during the die casting process the special layers in the upper part of the squirrel-cage rotor bars. The choice of the slot configuration and specific conductivity of the layers strengthening the effect of increasing the effective resistance of the rotor cage due to the skin effect which manifests itself at the beginning of starting, when the rotor current frequency is close to the industrial frequency, is of great importance. The IM's manufactured for the coal mining and gas extracting industry showed the improved performance characteristics and the high reliability level in severe applications [1]. Meanwhile, the capabilities of the further performance characteristics improvement of motors with the new rotor generation are still unused.

2. THE STATEMENT OF THE PROBLEM

The future trends associated with the optimal design of the rotor slots are directed on the following:

• the geometrical dimensions of the copper squirrel cage slots;
• to strike a compromise between components of the alloy for the upper layers distinguished by their specific conductivity;
• to strike a compromise between dimensions of the mentioned layer and the remainder part of the copper bar cross - section.

The object of the new research is to strike a compromise between the anisotropy components of the die-cast copper rotor bars by the use of the finite elements method (FEM). The mathematic statement of the problem reduces to distributing the induced currents in the two-layer rotor bar. The problems to be analyzed in the paper are associated with the third problem set above.

3. PRINCIPAL ASSUMPTIONS

A diagrammatic sketch of the rotor fragment being used for numeric computations of the rotor magnetic flux is shown in the Fig. 1.

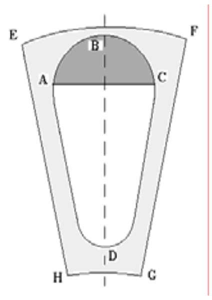

Fig. 1. Sectional view of the copper bar slot to be analyzed

The diagram represents a rotor tooth pitch EFGH with the arc EF disposed on the rotor surface and the arc HG on the rotor shaft surface. The rotor slot domain restricted by the demicircle ABC, 7.4 mm in diameter, contains the alloy characterized by the specific conductivity being varied in the range

$$\gamma_{ABC} \le \gamma_{Cu} .$$

The lower part of the slot domain (ACD) consists of the material which is characterized by the specific conductivity

$$\gamma_{ACD} = \gamma_{Cu} .$$

It is assumed that the left and right hand side tooth pitches are in the same conditions. Due to the symmetry of the magnetic fluxes relative to the dividing lines EH and FG the geometric boundary condition are taken as the homogeneous boundary conditions of the second order. In the case under consideration the partial derivatives of magnetic potential

$$\left.\frac{\partial A}{\partial h}\right|_{EH} = \left.\frac{\partial A}{\partial h}\right|_{FG} = 0 . \qquad (1)$$

4. ONE-DIMENSIONAL OPTIMIZATION BY NUMERIC COMPUTATIONS

The vector of magnetic potential corresponding to the air gap magnetic induction along the line EF taken as the boundary condition of the first order can be presented in the evident form

$$A\Big|_{EF} = \int_E^F B_\delta dx . \qquad (2)$$

Let us assume, approximately,

$$A\Big|_{EF} \approx B_\delta \cdot t_2 \sin \omega_1 t ,$$

where t_2 = tooth pitch on the rotor surface; ω_1 = angular frequency at the induction motor starting.

In a similar way, the magnetic potential along the line HG corresponding to magnetic induction on the rotor shaft surface can be represented as

$$A\Big|_{HG} \approx B_o \cdot t_2' \sin \omega_1 t , \qquad (3)$$

where t_2' = tooth pitch on the rotor surface.

As follows from the expression (1) the magnetic flux along the middle of the rotor teeth is propagated in radial direction only. Solution of the above boundary-value problem allows to determine the current density. The latter one is similar to the magnetic potential as for the single space component directed perpendicularly to the figure plane. The equivalent active resistance of the squirrel cage bar is determined by the expression

$$r_b = \frac{Q_b}{I_b} = \frac{\int_V (j/\gamma)^2 dv}{(\int_S jds)^2} = \frac{L_\delta \int_S (j/\gamma) ds}{(\int_S jds)^2} \qquad (4)$$

where I_b, Q_b = the full current and Joule's loss in the rotor bar, respectively:

$$I_b = \int_S jds , \quad Q_b = L_\delta \int_S (j^2/\gamma) ds ;$$

j = current density; V = volume of the rotor slot; L_δ = contour length.

Factor of the relative conductivity K_s reflecting the ratio

$$K_s = \gamma_{ABC} / \gamma_{ADC} = \gamma_{ABC} / \gamma_{Cu} \qquad (5)$$

was calculated in the range from 0 to 1. In the course of calculations the K_s - dependences of the Joule's loss and active resistance were analyzed.

5. DESIGN FINDINGS AND EXPERIMENTAL RESULTS

Construction of the IM finite element model and investigation of its magnetic fields, principal working parameters and characteristics was carried out for the explosion-proof induction motor 2ЭКВ3.5-210 type (210 kW, 1140 V, 1500 r.p.m.) supplied with the die-cast copper rotor (see Table 1). Analogous serial IM 2ЭКВ3.5-180 type (180 kW, 1140 V, 1500 r.p.m.) with the die-cast aluminum rotor cage is designed for the reduced power equal to 180 kW.

In the Fig. 2 is shown the cross-section of the induction motor rotor being designed in the region of the air gap. The complete computational model produced by the use of the FEM network generator contains 11,535 nodes and 22,968 elements.

Table 1

Design Data of the 2ЭКВ3.5-210 Type Induction Motor

Main indices	Stator	Rotor
Power, kW	210	
Voltage, V	1140 (star-connection)	
Number of poles	4	
Current, A	126.6	
Efficiency, %	90.9	
Power factor, cosφ	0.89	
External diameter, mm	320	195.6
Inner diameter, mm	198	105
Effective core length, mm	600	
Air gap length, mm	1.2	
Number of slots	48	45

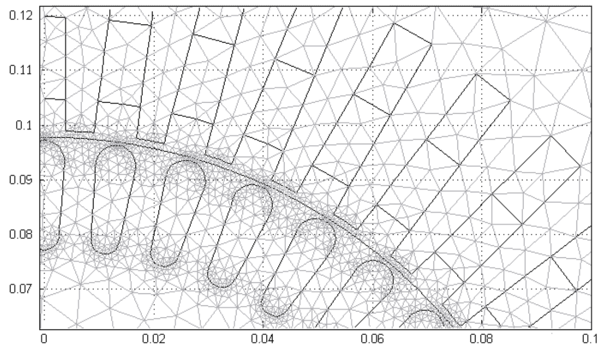

Fig. 2. Fragment of the finite element model destined for the 2ЭКВ3.5-210 type IM

The numerical calculations of the field distribution were based on the following assumptions:

• electroconductivity of the stator and rotor laminated cores is equal to zero;

• nonlinear characteristics of the ferromagnetic steel of the 2212 grade (relationship of the permeance vs magnetic induction), given in the tabulated form, can be obtained by the use the finite-difference approximation;

• the current density in the stator slots is expressible in terms of the formula

$$J_{1eff} = N_{1eff} \cdot I / S_w ,$$

where N_{1eff} = number of the effective conductors in the slot; I = phase current; S_w = wound stator slot cross-section;

• the current value in the rotor slots is determined with the use of the vector diagram for the IM rated conditions.

As a sample in the Fig. 3 is given the fragment of the designed magnetic field picture in the region of the IM air gap.

Distribution of the current density in the rotor slot is represented in the Fig. 4.

As it follows from the Fig. 4 the conductivity decrease of the upper layer results in increasing the current penetration depth into the rotor slot.

The designed dependences reflecting the anisotropy influence on the induction motor starting torque are shown in the Fig. 5.

As is apparent from the Fig. 5 the maximum values of the Joule's loss and active resistance in the rotor bars fall in the range between 0.5 > K_s >0.3. It is evident that the mentioned range coincides with the sought maximum value of the starting torque.

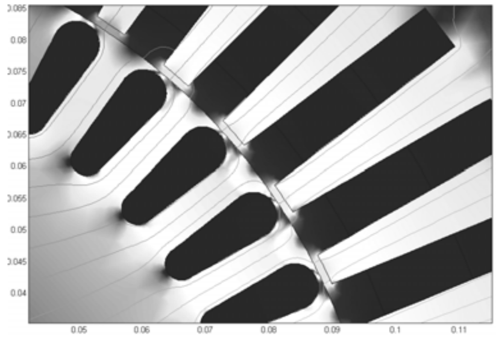

Fig. 3. Field distribution for the 2ЭКВ3.5-210 type IM at rated condition

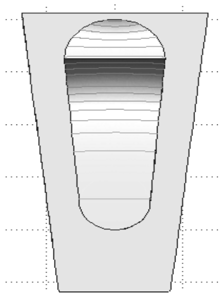

Fig. 4. Lines of equal current density at the factor $K_s = 0.4$

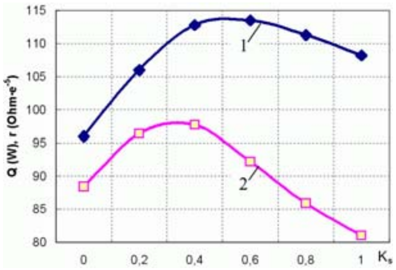

Fig. 5. Designed dependences: 1 - $Q_b(K_s)$; 2 - $r_b(K_s)$

The results of the designed findings are sufficient to allow the following important conclusions:

• the maximum values of the magnetic induction, in the range from 2.5…2.77 T, are observed in the bridges of the closed rotor slots that results to reducing the rotor leakage reactances (the favorable phenomenon);

• the saturation level of all the magnetic core parts is optimum attaining the maximum value equals 1.98 T in the tooth roots;

• the saturation levels on the field magnetic paths in the stator teeth, stator yoke and rotor shaft are equals 1.84 T, 1.62…1.95 T and 0.60 T, respectively.

As was apparent the eddy currents in the rotor shaft forth out the main magnetic flux reducing the magnetic induction to 0.40 T. At the designed current density (0.09 A/mm^2) the specific energy losses will be equals 400 W/m^3.

Electromagnetic torque was calculated by the use of magnetic strain tensor [4]. The designed electromagnetic torque characteristics versus rotor slip for the IMs ЭКВ3.5-180 type with the die-cast copper and aluminum rotor windings are shown in the Fig. 6.

As may be inferred from the Fig. 6 the IM equipped with the copper cage rotor has the advantage that its electromagnetic torque curve is more steep at the slips less than the critical value.

At the rated torque (1273 N·m) the mentioned feature involves, as compared with the serial IM, a decrease in the slip (from 0.067 to 0.032 p.u.) and rotor energy losses. The latter cause the efficiency rise by 2.5 per cent and a decrease in the rotor temperature. The breakdown torque, in the case under consideration, shows the increase from 2.950 to 3.306 N·m that is attributable to changes in the rotor leakage reactance. This is in agreement with the following extended consideration.

Really, the ratio between the current penetration in the bars of the copper and aluminum cages can be analyzed by the expression

$$\Delta_{Cu-Al} = \left(\frac{S_{Al}}{S_{Cu}} \cdot \frac{\gamma_{Al}}{\gamma_{Cu}} \right)^{0.5},$$

where S = rotor slip, γ = electric conductivity.

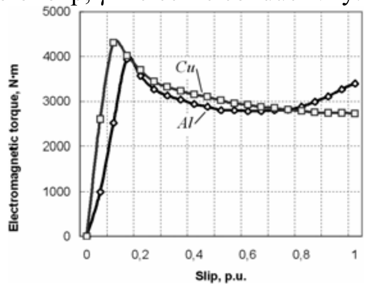

Fig. 6. Electromagnetic torque characteristics of the explosion-proof IMs

As is evident from the above expression, at the critical slips for the copper and aluminum cage rotors equals 0.12 and 0.182, respectively, and $\gamma_{Al} / \gamma_{Cu}$ =1.87 the ratio sought gives us the result equal to 0.90 S_o , in spite of the relationship

$$S_{cr\,Cu} < S_{\mathrm{cr\,Al}}$$

the equivalent current penetration in the slots of copper bars rotor cage will be less that leads to decreasing the rotor leakage reactance and increasing the breakdown torque.

The more detail analysis should be based on taking into account the influence of the slot shapes chosen, the temperature of the rotor winding, etc.

The locked – rotor torque was decreased by 24 per cent but the derivative of the electromagnetic torque with respect to the rotor slip does not change its sign in the slip range from 1.0 to its critical value. The mentioned feature influences favorably the transient processes at starting the IM.

6. CONCLUSIONS

It is shown that the induction motors supplied with the special "starting" layer disposed in the upper part the die-cast copper rotor bar possess with the maximum value of the starting torque at the relative conductivity factors in the range from 0.3 to 0.5.

The bench and service test of the prototype IM (2ЭКВ3.5-210) produced the main performance data closely related to the findings designed.

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