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RESEARCH OF INDUCTION IN THE AIR GAP OF AN INDUCTION MOTOR TO DETERMINE MAXIMUM ENERGY CHARACTERISTICS

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Annotation. *Induction motors with squirrel-cage rotor are today the most frequently used motors in modern electric drive systems of the mining industry. They are used in various mechanisms, devices, the operation of some of which is associated with difficult start-up and overload modes, which are inherent in the operation of coal harvesters, lifting mechanisms, and conveyors.*

Recently, the problem of optimal design of induction motors (IM) has come to the fore. In the conditions of competition between IM manufacturers, it is necessary to create energy-efficient motors with high energy performance.

To achieve energy efficiency, along with the use of modern materials and an increase in active dimensions, there is a relatively inexpensive way to increase the overload capacity of the AC without changing the dimensions of the motor itself. This involves forming a grooved rotor zone, when the developer performs parametric optimization to obtain the final design.

As a rule, modern design departments engaged in the design of induction motors have at their disposal software for calculating the electromagnetic field using the finite element method (for example, the ANSYS Maxwell program). When using such programs, there are all the prerequisites for successfully solving the problem.

Thus, based on the above, the relevance of the research topic is determined by the need to create induction motors with a squirrel-cage rotor that have high overload characteristics , energy characteristics, and starting torque, which are advantages over competitors.

The goal of the scientific work is to analyze the existing analogue (basic version) of the IM, using progressive design techniques, to propose an efficient motor, varying only the parameters of the rotor slot zone.

Keywords: *induction motor, slot geometry, magnetic induction, starting and maximum torque ratios, overload capacity.*

Introduction. Induction squirrel-cage motors form the basis of modern electric drives in the mining industry. They consume most of the electricity consumed by all electric motors combined. Such motors are subject to additional requirements related to their operating conditions: energy efficiency (efficiency and cosφ), high overload capacity (multiplicity of maximum torque), high starting characteristics (multiplicity of starting torque).

In this regard, the scientific work aims to show that by modeling the electromagnetic field, choosing the geometric dimensions of the slots of the rotor of an induction motor, it is possible to obtain the necessary characteristics of the IM.

To achieve it, the following tasks must be solved:

1. To review the current state of the issue.
2. Choose a method for studying the electromagnetic field in induction motors.
3. To find out the influence of the shape of the rotor slots on the parameters of an induction motor.
4. Evaluate the currently existing recommendations for designing the rotor magnetic circuit.
5. Carry out a series of electromagnetic calculations with different geometric dimensions of the rotor slot.
6. Develop recommendations for designing rotor slots for an energy-efficient squirrel-cage induction motor.

Analytical review. At this time, many manufacturers of induction machines have set themselves the task of developing new energy-efficient induction motors. But the main trends in increasing the energy efficiency of induction motors are the use of new design and technological solutions aimed at reducing known types of losses in an electric machine, as well as modern calculation methods. At the same time, practically no attention is paid to optimizing the magnetic circuit of AC electric machines. [1, 2].

The assessment of the efficiency of electromechanical energy conversion in three-phase induction motors cannot be performed correctly without considering and solving the equations of the electromagnetic field. An effective method for solving the problems is the numerical method of finite elements [3]. This method reduces the boundary condition of the problem to a variational one, when instead of solving the differential equations of the field in partial derivatives, the extremum of the functional is sought

$$W(A) = \frac{1}{2}\int \left|vA\right|^2 ds \tag{1}$$

To simplify the solution of the electromagnetic field equations, it is customary to introduce an intermediate variable, which is the vector magnetic potential. This auxiliary function is introduced by the following relation [4]

$$B = rotA \tag{2}$$

Despite the fact that the electromagnetic field in induction machines is three-dimensional, we will use its two-dimensional model, assuming that the magnetic field pattern repeats along the axis of rotation.

Taking into account the relation (2), it is clear that the vector magnetic potential defines two vectors: *B* and *H*. According to the principle of minimum potential energy, the potential distribution in an electric machine should be such as to minimize the stored energy.

When finding the field energy, integration is performed over the entire two-dimensional region. In the general case, when a current flows through the winding of an induction motor located in the slots of the magnetic core, the field created by it is described by Poisson's equation [5].

For calculations of the EMF of a magnetic system acting on a selected volume, the theory of electromagnetism suggests the following methods: by increasing the magnetic energy of the system; by the volumetric or surface density of the EMF. In this case, the EMF and moments can be strictly and unambiguously determined only on the basis of calculations of the electromagnetic field. That is, in all three cases it is assumed that the electromagnetic field is numerically or analytically calculated for a given moment of time t , while the moving part of the IM or other magnetic system occupies a certain position relative to its stationary part.

Due to the increased capabilities of computing and the development of numerical methods for calculating electromagnetic fields, the most widely used methods for calculating EMF and moments are those that use the concept of the tension tensor [6].

To solve the problem, you can use any standard finite element method package. The work used the ANSYS Maxwell program, which allows you to solve such problems quite effectively.

Harmonic analysis of the air gap induction curve in an induction motor assumes the presence of both odd and even harmonics in the spectrum. The function describing the air gap induction curve can be represented as:

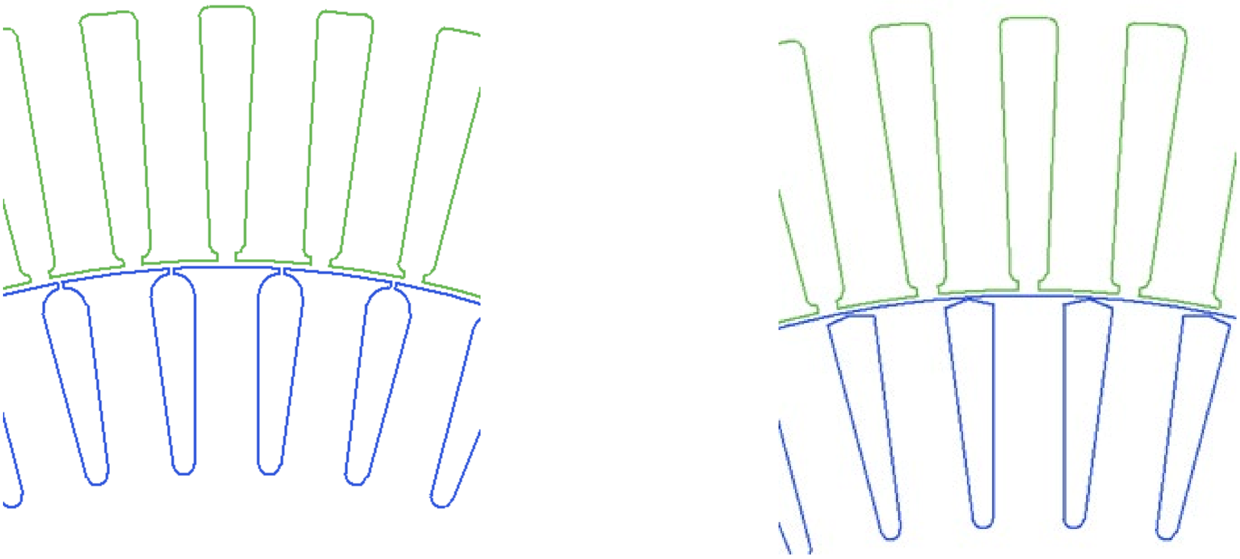
$$F(t) = A_0 + \sum_k (B_k \sin(kt\frac{2\pi}{|a|+b} + C_k \cos(kt\frac{2\pi}{|a|+b})) \tag{3}$$

where *A, B, C* are the coefficients of the Fourier series, a , b are the limits of the period of the function, *k is* the harmonic number.

Using expression (3), the author of the program in the Mathcad environment selects from the array of values of induction in the air gap the harmonic components of any order.

The harmonic composition of the field of an induction motor contains winding harmonics of order $6 \cdot k \pm 1$, stator tooth harmonics of order $\frac{k \cdot Z_1}{p} \pm 1$ (the winding coefficients of these harmonics are equal to the winding coefficient of the first harmonic), rotor tooth harmonics of order $\frac{k \cdot Z_2}{p} \pm 1$ (k -any positive integer), saturation harmonics, which are caused by the nonlinear dependence between magnetic induction and magnetizing current. (These include non-winding harmonics that are multiples of three) [7]. Saturation harmonics rotate at a synchronous speed, and winding harmonics with a speed equal to the ratio of the synchronous frequency to the harmonic order.

Research part. The task that arose in the research process was to find the optimal geometry of the rotor slots of the motor being modernized to increase the overload capacity (multiplicity of maximum torque) and starting characteristics (multiplicity of starting torque). In this case, the geometry of the slots and the stator winding did not change, and the mass of aluminum of the short-circuited rotor winding should not be more than the basic version. Having made a number of search calculations, a version of the motor with a new geometry of the tooth zone was obtained (Fig. 1).



a *b*

Fig. 1 - Toothed zone of the basic version (*a*) and Tooth zone of the modernized motor (*b*)

The main parameters of the motors have been determined and are presented in Table 1.

Table 1. Results of electromagnetic calculations

	Rnom, kW	Efficiency, %	Inom, A.	cosφ	Kmm	Kmp	Kip
Base motor	130	93.8	136.5	0.85	5.3	2.6	10.3
Modernized motor	130	94.0	134.9	0.86	7.0	4.5	12.0

The magnetic induction curves in the air gap of the base and the modernized motor in the nominal motor mode were calculated (Fig. 2, 3). It can be seen that the spectral composition of the electromagnetic field of the modernized motor has changed significantly compared to the base version of the electric motor.

The reverse field of the fifth harmonic at $s = 0 \div 1$ creates a negative moment M_5 (braking mode); the direct field of the seventh harmonic at $0.857 < s < 1$ creates a positive moment M_7 (motor mode), and at $s < 0.857$ — a negative moment M_7 (generator mode). The greatest danger is represented by parasitic induction moments with a short-circuited rotor winding, because in this case the currents induced by the higher harmonics of the magnetic field in the rotor rods have a small electrical resistance. The results of determining the amplitude of the first and higher harmonics are presented in Table 2.

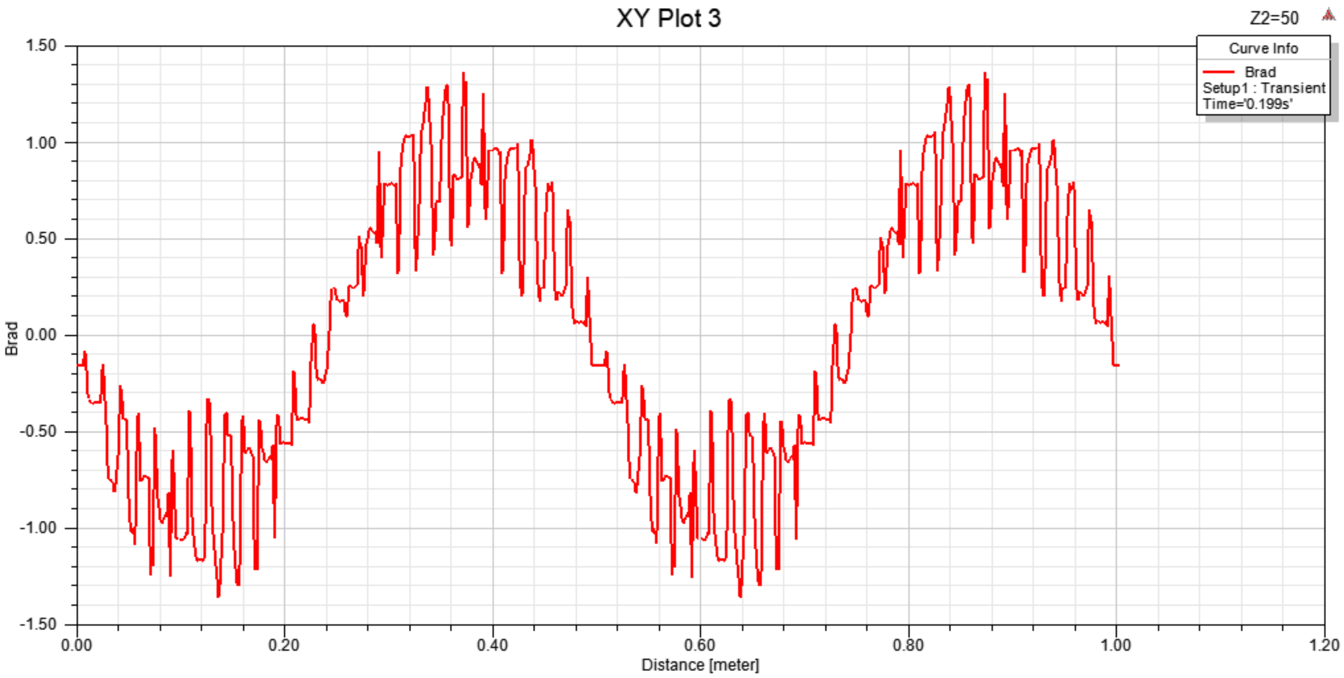


Fig. 2 - Distribution of the magnetic induction curve in the air gap at the rated load of the base motor

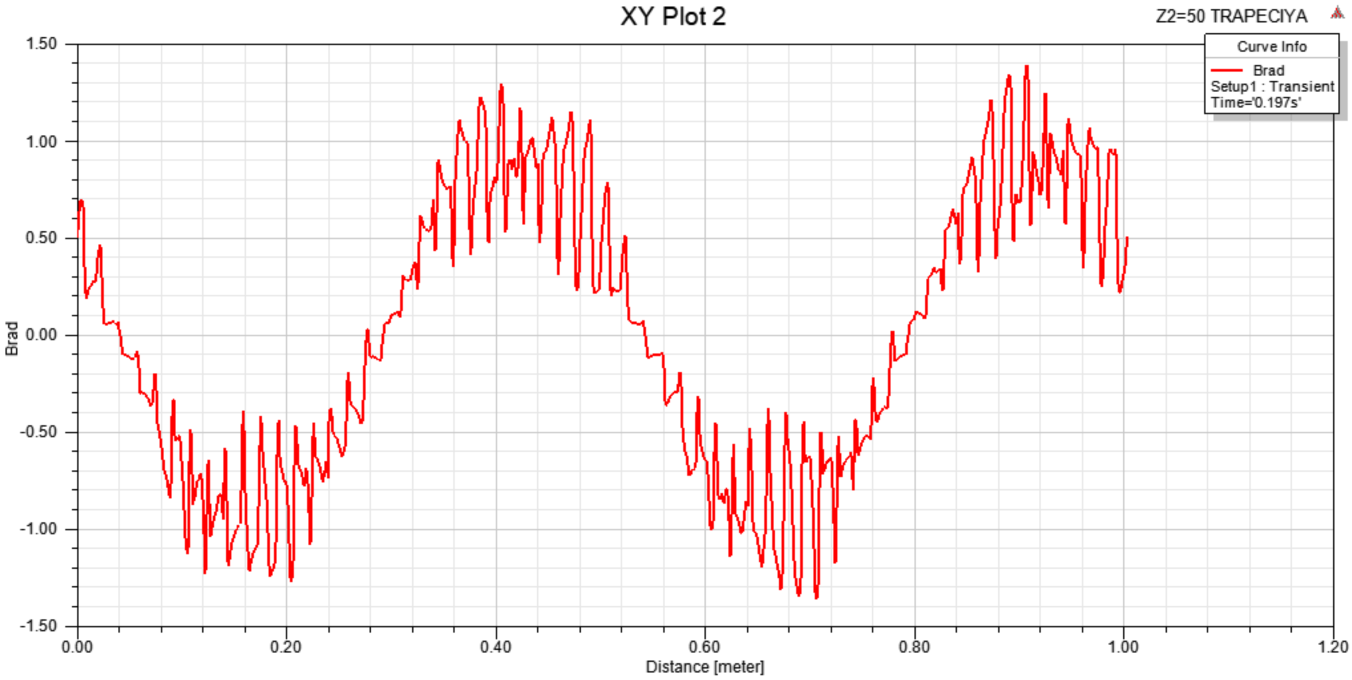


Fig. 3 - Distribution of the magnetic induction curve in the air gap at rated load of the motor being modernized

Table 2. Amplitude of harmonic components of induction in the gap

	1st harmonic, *Tl*	3rd harmonic, *Tl*	5th harmonic, *Tl*	7th harmonic, *Tl*
Base motor	0.9753	0.051	0.02	0.015
Modernized motor	0.976	0.045	0.018	0.011

The reduction in the amplitudes of higher harmonics in the modernized version indicates that the magnetic induction curve in the air gap of the modernized motor has a shape closer to a sinusoid than that of the base motor. This allows to reduce magnetic pulsations, noise, vibration of the motor, and improve its energy characteristics.

Conclusions. The computational experiment conducted by the finite element method allowed us to refine the rational geometry of the rotor slots to achieve the task of obtaining an motor with higher overload capacity and starting torque. The influence of the geometry of the rotor tooth zone on the magnetic induction curve in the air gap was determined.

Recommendations can be made regarding the design of energy-efficient induction motors. First of all, when comparing several design samples of IM, it is necessary to use the analysis of the harmonic components of the induction curve in the air gap in different modes of motor operation (starting, maximum load, nominal load). This will make it possible to obtain an motor with high characteristics at the design stage and save money on the manufacture of experimental samples of IM.

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