МОДЕЛЮВАННЯ ТА ОПТИМІЗАЦІЯ В ТЕХНОЛОГІЇ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ

SIMULATION AND OPTIMIZATION IN TECHNOLOGY OF CONSTRUCTION MATERIALS

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MATHEMATICAL MODELING OF TRANSIENT PROCESSES IN A SQUIRREL-CAGE INDUCTION MOTOR USING A FIELD-BASED APPROACH

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ПЕРЕХІДНИХ ПРОЦЕСІВ В АСИНХРОННОМУ ДВИГУНІ З КОРОТКОЗАМКНУТОЮ КЛІТКОЮ В ПОЛЬОВІЙ ПОСТАНОВЦІ

The paper presents a mathematical model of an induction motor (IM) with a squirrel-cage in a field-based formulation. The primary objective of the study is to develop a model that enables accurate calculations of the electromagnetic and electromechanical characteristics of the motor in quasi-static and transient operating modes. The development of the IM model was based on the following simplifications and assumptions: the magnetic field within the active region of the machine is considered planar-parallel; the IM's magnetic core is assumed to have infinite resistance, meaning that eddy currents in the stator and rotor steel are absent, and hysteresis is not considered. The model accounts for the nonlinearity of the magnetic core due to the magnetization curve, rotor slot skewing, rotor rotation, rotor short-circuit rings, and the inductance of the stator winding end turns.

The finite element method (FEM) is used for the numerical solution of the differential equations, taking into account the geometric parameters of the IM. For the calculation of the IM's mechanical characteristics, the magnetic field stress tensor method is applied.

***Keywords**: squirrel-cage induction motor; finite element method; electromagnetic torque; transient process.*

Дослідження, представлене у статті, присвячене розробці математичної моделі асинхронного двигуна (АД) з короткозамкнутою кліткою. Метою роботи є вдосконалення процесу розрахунку електромагнітних і електромеханічних характеристик двигуна в різних режимах його роботи, зокрема в квазістатичних та перехідних процесах. У моделі враховуються кілька спрощень, таких як плоскопаралельність магнітного поля в активній зоні двигуна та нескінченний магнітний опір, що дозволяє ігнорувати вихрові струми в металі статора та ротора.

Робота використовує метод скінченних елементів (МСЕ) для вирішення диференційних рівнянь, що описують електромагнітне поле та інші фізичні явища в електричній машині. Завдяки цьому методу стає можливим врахування нелінійності магнітопроводу, впливу скосу пазів ротора та індуктивності лобових частин обмотки. Застосований підхід дозволяє отримати точніші результати для розрахунку механічних характеристик АД, що є критичним для забезпечення ефективної роботи двигуна в умовах зміни навантаження та частоти обертання.

Особливу увагу приділено перехідним процесам, які є найбільш складними для аналізу. У статті детально розглядається математична модель, заснована на рівняннях Максвелла, що дозволяє моделювати розподіл магнітного поля у поперечному перерізі двигуна. Запропонована модель демонструє високу точність результатів, що корелює з експериментальними даними, зокрема при моделюванні процесів короткого замикання та холостого ходу.

Отримані результати дозволяють більш детально аналізувати робочі режими АД та оптимізувати їх конструкції. На основі запропонованої моделі проведено симуляції різних режимів роботи двигуна, результати яких продемонстрували, що перехідні процеси, такі як пуск двигуна та робота при номінальному навантаженні, можуть бути точно змодельовані та досліджені.

Зроблені висновки, на основі проведених досліджень, підтверджують ефективність застосування польових моделей для аналізу роботи асинхронних двигунів, що значно підвищує точність прогнозування електромагнітних та електромеханічних характеристик у різних режимах роботи.

***Ключові слова**: асинхронний двигун з короткозамкнутою кліткою; метод скінчених елементів; електромагнітний момент; перехідний процес.*

Problem's formulation

Electric machines are the main type of electromechanical energy conversion devices. Practically all electrical energy is produced mechanically with the help of generators. More than 60 % of all electricity produced is converted back into mechanical electricity with the help of electric motors. Among the various types of electric motors, asynchronous motors (AD) are the most widely used due to their advantages, such as simplicity of design, high energy performance, and minimal operating costs.

The use of AD is constantly expanding, and the scope of application is increasing. The peculiarities of their work differ from the previously generally accepted ones. The main ones are: non-sinusoidal nature of the supply voltage; variable rotation frequency; variable and uneven redistribution of losses in active parts; in some cases, it is necessary to take into account the parameters of the control device and the parameters of the power line; power supply from a source of commensurate power. Therefore, the development and improvement of mathematical models for the study of quasi-static and transient processes is relevant.

Analysis of recent research and publications

For the study of quasi-static and transient processes, mathematical models in the form of electric circuits described by differential equations and field models based on the solution of Maxwell's equations are widely used. Field mathematical models allow you to take into account both external electrical circuits and design features. The finite element method (FEM) is used for numerical calculations of such models.

A significant contribution to the use of the field approach was made by Antero Arkkio [1—6]. He developed methods for the analysis of asynchronous motors through the joint solution of the equations of the magnetic field and the equations of electric circuits. AD was viewed in cross-section in a two-dimensional setting, but three-dimensional features such as the bevel of the rotor grooves, the stator fronts, and the rotor rings were taken into account. The developed model was used to calculate motors with a short-circuited winding and a massive ferromagnetic rotor. The simulation results are in good agreement with the experimental data, demonstrating the high accuracy and efficiency of the proposed approach.

The paper [7] gives a detailed analysis of electric machines in the field setting. The authors consider the various stages of modeling, including defining machine geometry, specifying material properties, creating a finite element mesh, and setting boundary conditions. Algorithms for solving the equations are described, including the generation and optimization of the finite element mesh, as well as the analysis of the calculation results, such as the distribution of the magnetic flux and the density of the magnetic flux in AD. Considered the possibilities of automating the calculation process, which significantly reduces the time and complexity of the analysis.

The work [8] shows the design of electric machines based on the field approach. Considered Maxwell's equations in integral and differential form, and their application in the design of electric machines. Methods of analysis and calculation of electromagnetic fields that arise in machines, including moment calculation. The influence of materials, in particular electrical steels, on the efficiency and reliability of machines is considered. Methods of testing and maintenance are shown, which ensure durability and stable operation of electric machines. Design methods that take into account the interaction between electric machines and static converters are presented.

In the work of the authors Ravi Kumar Jujjuvarapu and Basavaraja Banakara [9], the electromagnetic and thermal characteristics of AD were investigated by means of mathematical modeling in a field setting using the Arcchio model to estimate the magnetic flux, electromagnetic moment, losses in the stator and rotor, as well as temperature distribution. Using the COMSOL Multiphysics software, the authors analyzed the transient electromagnetic and electromechanical characteristics. The conclusions of the study show that the use of Arkkio models allows to significantly improve the accuracy of modeling and forecasting the characteristics of asynchronous motors.

Summarizing the results of the research analysis, it was established that the use of field models allows to calculate the distribution of the magnetic field in the cross section of the AD, electromagnetic and electromechanical characteristics. The obtained results are well adjusted with the experimental data. Therefore, the use of mathematical models in the field setting allows you to investigate in detail the different operating modes of AD of different designs and to optimize them.

Formulation of the study purpose

The purpose of the study is to develop a mathematical model of an induction motor (AD) in a field setting, which allows calculations of the electromagnetic and electromechanical characteristics of the motor. This involves taking into account the external electric circuits, the frontal parts of the stator windings, short-circuited circuits, the distribution of induced currents in the rotor rods with a bevel, which occurs due to the rotational movement of the stator field relative to the rotor.

Presenting main material

In general, the electromagnetic field for anisotropic nonlinear media is described by a system of Maxwell's differential equations, which has the form:

$$\begin{aligned} rot\vec{H} &= \vec{J} + \frac{\partial \vec{D}}{\partial t}; \\ rot\vec{E} &= -\partial \vec{B}/\partial t; \\ div\vec{D} &= \rho; \\ div\vec{B} &= 0, \end{aligned} \tag{1}$$

where $\vec{H}$ — is the magnetic field intensity; $\vec{J}$ — the current density; $\vec{D}$ — the electric flux density; $\vec{E}$ — the electric field intensity; $\vec{B}$ — the magnetic flux density; ρ — the electric charge density.

The Maxwell equations (1) are complemented by the constitutive equations that describe the electromagnetic properties of the material medium. These equations are as follows:

$$\begin{gathered}\vec{D} = \sigma\vec{E};\\ \vec{B} = \mu\vec{H};\\ \vec{J} = \sigma\vec{E},\end{gathered} \tag{2}$$

where ε — is the permittivity, which may depend on the electric field E; μ — is the permeability; σ — is the electrical conductivity.

Given that $\partial\vec{D}/\partial t \ll \vec{J}$, the first equation (1) takes the form:

$$rot\vec{H} = \vec{J}.$$

In the proposed form, the system of equations (2) is usually not solved. As a rule, it turns into another, in which the vectors $\vec{E}, \vec{B}$ and $\vec{H}$ are replaced by auxiliary functions — a scalar or vector potential.

The electromagnetic field can be defined through the vector magnetic potential, which is related to the magnetic induction by the ratio:

$$\vec{B} = rot\vec{A}. \tag{3}$$

By substituting its expression in terms of the vector magnetic potential (3) instead of the magnetic induction into the second equation of the system (1), we obtain:

$$rot\vec{E} + \frac{\partial\vec{B}}{\partial t} = rot\left[\vec{E} + \frac{\partial\vec{A}}{\partial t}\right] = 0. \tag{4}$$

The expression in (4) $\vec{E} + \frac{\partial\vec{A}}{\partial t} = -grad\phi$ is a scalar gradient, where ϕ – is an electric scalar potential. Then (4) has the form:

$$\vec{E} = -\frac{\partial\vec{A}}{\partial t} - grad\phi. \tag{5}$$

By multiplying equation (5) by the electrical conductivity of the medium σ, obtained an expression from which the current density into the medium can be determined:

$$\vec{J} = -\sigma\frac{\partial\vec{A}}{\partial t} - grad(\sigma\phi). \tag{6}$$

If there are moving parts in the medium and leakages $\vec{J}_S$ on the side, then equation (6) is supplemented with an expression for the current density:

$$\vec{J}_v = \sigma\vec{V} \times \vec{B},$$

where $\vec{V}$ – linear velocity.

By adding in (6) $\vec{J}_S$ and $\vec{J}_v$ we will get:

$$\vec{J} = -\sigma\frac{\partial\vec{A}}{\partial t} - grad(\sigma\phi) + \sigma\vec{V} \times \vec{B} + \vec{J}_S.$$

Substituting $\vec{J}$ into the second equation (1), we get:

$$rot\vec{H} = -\sigma\frac{\partial\vec{A}}{\partial t} - grad(\sigma\phi) + \sigma\vec{V} \times \vec{B} + \vec{J}_S. \tag{7}$$

The magnetic induction of a ferromagnetic material is defined as:

$$\vec{B} = \mu\vec{H} + \vec{B}_0,$$

where $\vec{B}_0$ — residual magnetic induction.

We accept that $\vec{B}_0 \to 0$ then:

$$\vec{B} = \mu\vec{H},$$

or:

$$\vec{H} = \frac{1}{\mu}\vec{B}, \tag{8}$$

where ${}^{1}/_{\mu} = \nu$ — magnetic resistance of the material.

By substituting expression (8) into (7) and performing the transformation taking into equation (3), we obtain the field equation written with respect to the vector magnetic potential:

$$-\nabla \times \nu\nabla \times \vec{A} = -\sigma\frac{\partial \vec{A}}{\partial t} - grad(\sigma\phi) + \sigma\vec{V}\times\vec{B} + \vec{J}_S. \tag{9}$$

The following simplifications and assumptions were used when developing the AD model: the magnetic field within the active space of the machine is plane-parallel; the AD magnet wire has infinite resistance, that is, there are no Eddy currents in the steel and hysteresis is not taken into account.

Because the field is plane-parallel, then if the z axis of the coordinate system is oriented parallel to the AD shaft axis, then the magnetic field induction vector $\vec{B}$ will lie in the x-y axis, that is, in the plane of the cross-section of the machine. Then the current density vector $\vec{J}$ and vector magnetic potential $\vec{A}$ will be parallel to the z axis. This allows us to move from vectors to scalar quantities in equation (9).

An induction motor has a complex design, so each element of the design is described by a different equation. If the first part of the equation is common to all structural elements, the second part is different. Therefore, let's present equation (9) for each structural element separately in a two-dimensional formulation [10]:

$$-\nabla\left(\nu\nabla\vec{A}\right) = \begin{cases} 0 - in\ the\ air\ gap; \\ 0 - in\ the\ stator\ core; \\ \frac{N_{W1} i_{01}}{S_{W1}} - in\ the\ stator\ slot; \\ \sigma\nu\left(\frac{\partial A}{\partial x} - \frac{\partial A}{\partial y}\right) - in\ the\ rotor\ core; \\ \sigma\left(-\frac{\partial A}{\partial t} + \nu\left(\frac{\partial A}{\partial x} - \frac{\partial A}{\partial y}\right) + \frac{u_t}{l_t}\right) - in\ the\ rotor\ bar; \\ \sigma\left(-\frac{\partial A}{\partial t} + \nu\left(\frac{\partial A}{\partial x} - \frac{\partial A}{\partial y}\right)\right) - in\ the\ rotor\ shaft, \end{cases} \tag{10}$$

where N_{W1} — the number of turns in the stator winding coil; i_{01} — the current flowing through the stator winding coil; S_{W1}— the cross-sectional area of the stator winding coil.; v — the linear speed of rotation of the rotor; u_t — voltage on the rotor bar; l_t — the length of the rotor bar.

Equation (10) is supplemented by the equilibrium equation of the phase voltage of the stator winding:

$$u_{01} = r_{01} i_{01} + \frac{d\Psi_{01}}{dt},$$

where u_{01} — is the instantaneous voltage value of the stator winding phase; r_{01} — is the active resistance of the stator winding phase; i_{01} — is the current in the stator winding; Ψ_{01} — complete flux coupling of the stator winding phase.

For a three-phase AD winding through the magnetic induction vector and taking into account the dissipation inductance of the front parts of the stator winding, formula (10) takes the form:

$$\{u_{01}\} = \{r_{01}\}\{i_{01}\} + \frac{N_{W1} l}{S_{W1}}\left\{\int_{S_{W1}} \frac{\partial A}{\partial t} dS_{W1}\right\} + L_{1l}\frac{d\{i_{01}\}}{dt},$$

where $\{u\}$ — stator phase voltage vectors; $\{i\}$ — vector of phase currents of the stator winding; $[r]$ — winding resistance matrices; L_{1l} — dissipation inductance of the front parts of the windings.

We supplement the obtained equations with the equation for the electromagnetic moment. The electromagnetic moment can be determined by one of three known methods: according to Ampere's formula, the method of virtual movement of the moving part, and the method of the tension tensor of the magnetic field vectors [7]. Among the mentioned methods, the magnetic field tension tensor method is the most effective and economical, since its application is not associated with time-consuming integration over the volume of the body under consideration. The integration is carried out only over the surface, and in the case of a two-dimensional problem — along a line covering the calculation area, therefore, in this work, the method of the magnetic field tension tensor is used to calculate the mechanical characteristics of AD, which is determined by the formula:

$$M = \frac{D_r + l_\partial}{2\mu_0} \oint_S B_n B_t dS,$$

where D_r — rotor diameter; l_∂ — air gap width; B_n, B_t — respectively, the normal and tangential components of the magnetic induction vector relative to the rotor surface. The integration is carried out over the surface that surrounds the rotor and passes through the center of the air gap.

Equation(10) are supplemented by boundary conditions — the values of the vector potential at the outer boundary of the region. We assume a homogeneous boundary condition of the first kind $A_B=0$, which means neglecting the magnetic fluxes of dispersion outside the calculation domain. was chosen as the object of research AD 4AA63A4U3 the main parameters of which are given in the tabl. 1 [11].

Table 1. The main parameters of AD 4AA63A4U3

Electric drive type	2p	U_L, B	D_{a1} /D_{i1}, mm/mm	l_1, mm		δ, mm	Z_1/Z_2	S_s	n/a
4AA63A4У3	4	380	100/61	56		0,25	24/18	169	1/1

Continuation of *Table 1*

d/d''	K_w	l_ω, mm	r_1, Ohm	a_k/b_k, mm/mm	Slot skew, mm
0,38/0,42	0,966	272	29	4,5/11,8	8,0

Modeling is carried out in ANSYS Maxwell student version. The main element of the complex model is the electrodynamic 2D model of the engine, obtained using the special tool RMxprt from the ANSYS Maxwell package.

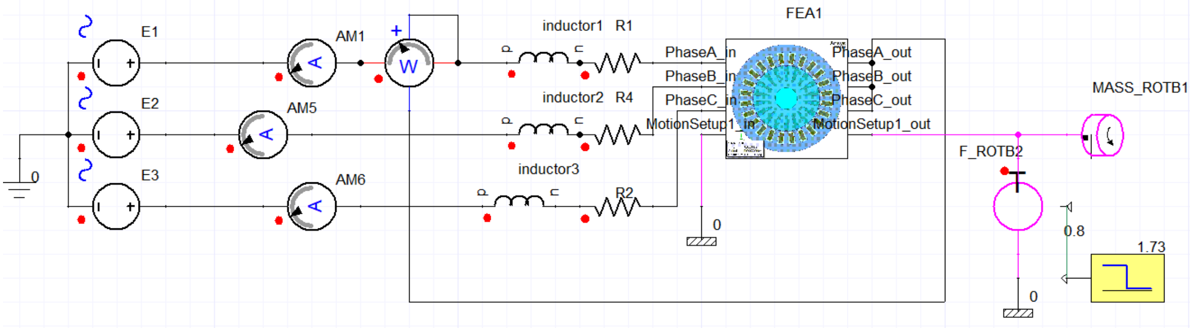
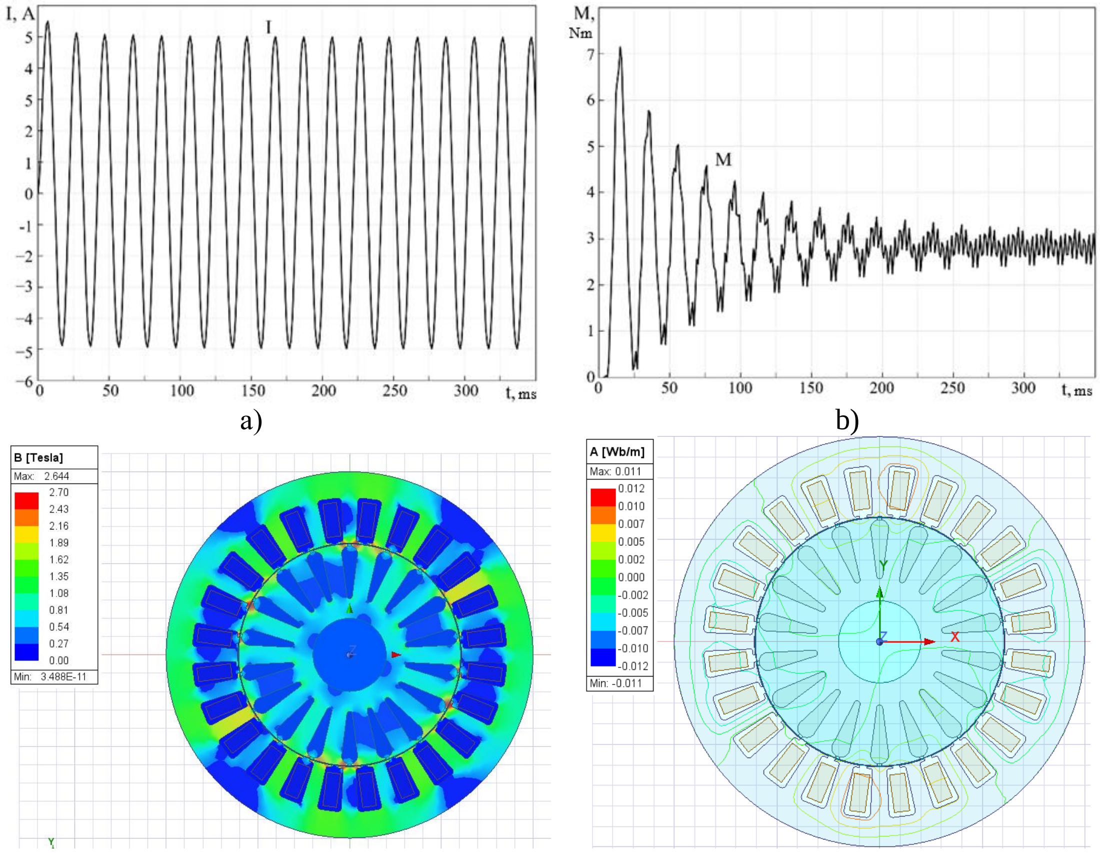


Fig. 1. Electrical diagram of the AD model

This method of modeling in Maxwell is the fastest and most convenient. In RMxprt, you need to set the main technical parameters of the engine, such as geometric dimensions of its structural elements, materials, nominal data (a complete list of such parameters for 4A series engines is available in the reference [8]). From the resulting rmxprt model, Maxwell can automatically build a finite element 2D or 3D engine model. Compilation of the main circuit (Fig. 1) of the control system model is carried out in ANSYS Simplorer from standard functional blocks: a source of three-phase sinusoidal voltage, measuring devices, control blocks for the task of mechanical inertia and nominal torque AD. The circuit operation algorithm (Fig. 1) is as follows: three single-phase sinusoidal generators (E1, E2, E3) are connected in a "star" type with a middle point with a set phase shift relative to each other by 120°. Thus, a three-phase power supply network for a three-phase AD was formed. The sinusoidal voltage generated through the ammeters (AM1, AM2, AM3) and the wattmeter (W) is fed to the series-connected inductance (inductor 1, 2, 3) and resistor (R1, R2, R3). The value of the resistor corresponds to the resistance of the AD winding, and the inductance corresponds to the field dissipation resistance of the front parts of the AD. The AD model is presented in the form of an FEA1 block.

The developed mathematical model allows conducting research of quasi-static and transient processes.

In fig. 2 shows the results of modeling the short-circuit mode, from which it can be seen that the current amplitude (Fig. 2, a) is 5 A. The permanent electromagnetic moment (Fig. 2, b) is 2.8 Nm. The distribution of magnetic induction in AD is shown in fig. 2, c, from which it can be seen that in the short-circuit mode, the maximum value of the magnetic induction in the stator teeth is 2 T, in the stator spoke 1.6 T, in the rotor grooves 0.8 T, in the rotor back 0.6 T [12]. Lines of vector magnetic potential (Fig. 2, d) are distributed along the poles of AD and in the short-circuit mode are displaced from the rotor and pass along the upper parts of the rods of the short-circuited cage. In this mode, the magnetic system of the rotor is unsaturated with AD.

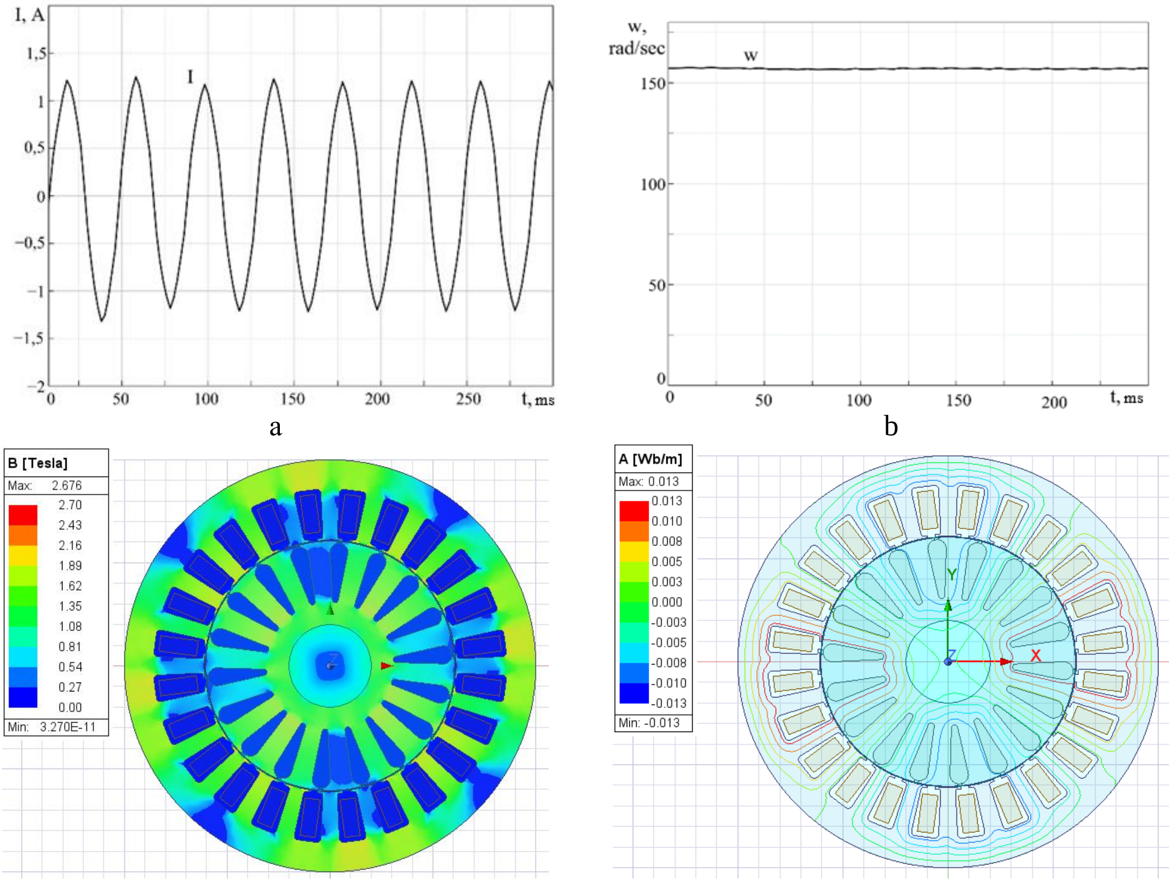


a) b)

c) d)

Fig. 2. Transient characteristics of AD in the short-circuit mode, where: a — the current, b — dynamic moment, c — distribution of the magnetic induction, d — distribution of the vector magnetic potential

In fig. 3 shows the results of the simulation of the ideal idling mode of AD. The constant value of the current amplitude is 1.2 A (Fig. 3, a) at an angular velocity of 157 rad/s (Fig. 3, b). Rozthe division of magnetic induction in AD is shown in fig. 3, c, from which it can be seen that the maximum value of magnetic induction in the teeth of the stator is 1.8 T, in the spoke of the stator 1.7 T, in the grooves of the rotor 1.65 T, in the back of the rotor 1.4 T. The lines of the vector magnetic potential (Fig. 3, d) are distributed along the poles of AD and completely cover the rods of the short-circuited cage [12]. In this mode, the AD magnetic system is saturated.



a b

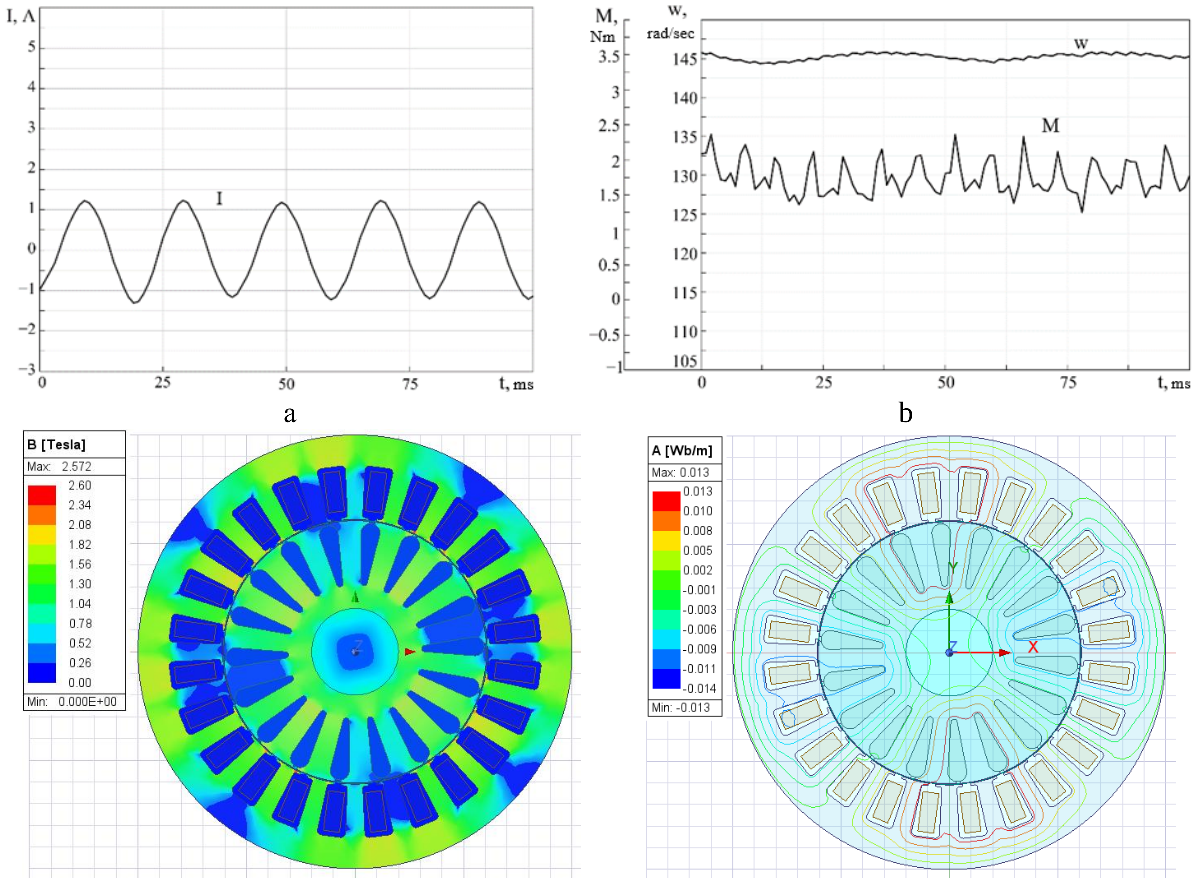
c d

Fig. 3. Transient characteristics of AD in the mode of ideal idling, where: a — current, b — speed, c — distribution of the magnetic induction in the electric machine, d — distribution of the magnetic potential

In fig. 4 shows the results of modeling the operating mode of the AD with a nominal load. From fig. 4, and it can be seen that the amplitude value of the current is 1.25 A. The angular velocity (Fig. 4, b) is 145 rad/s and tooth harmonics are superimposed on it. The average value of the moment (Fig. 4, b) is 1.75 Nm, and its value is affected by the bevel of the grooves and the number of stator and rotor teeth.

The distribution of magnetic induction in AD is shown in fig. 4, c, from which it can be seen that the maximum value of magnetic induction in the stator teeth is 1.9 T, in the back of the stator — 1.7 T, in the grooves of the rotor — 1.82 T, in the back of the rotor — 1.5 T. The lines of the vector magnetic potential (Fig. 4, d) are distributed in the poles of AD and completely cover the rods of the short-circuited cage and are displaced from the rotor shaft.

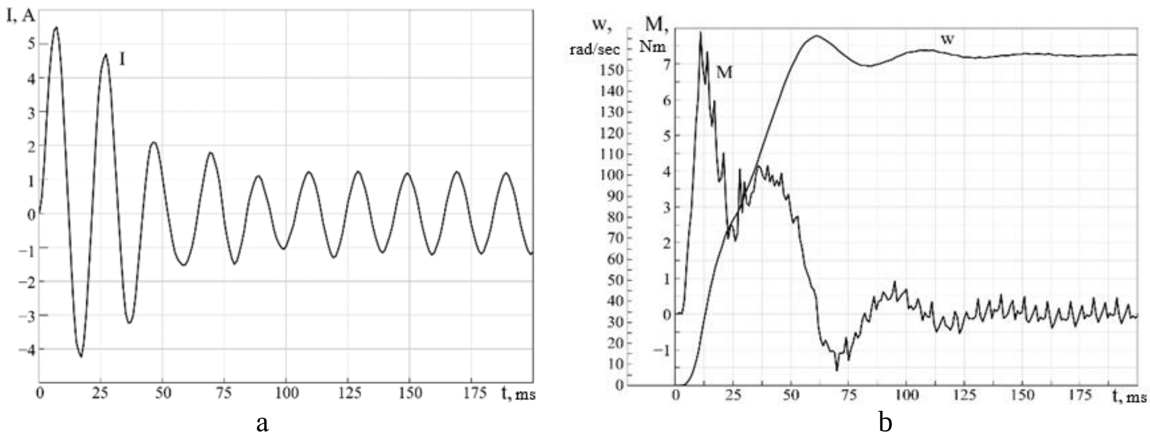
In fig. 5 a, b show the transient process of AD start-up, from which it can be seen that the maximumthe amplitude value of the start is 5.5 A, the duration of the start to a constant value is 150 ms. At the beginning of the start-up, the maximum value of the electromagnetic moment is 7.9 Nm and has a clearly expressed maximum at 37.5 ms, which is 3.75 Nm. The angular speed increases smoothly and when the ideal idle speed is reached, it turns into damped oscillations.



a b

c d

Fig. 4. Characteristics of AD in the restart mode with established parameters, where a — current, b — speed, c — distribution of magnetic induction in the electric machine, d — distribution of the magnetic potential



a b

Fig. 5. Transient processes of AD in the start-up mode without load, where a — current, b — speed and moment

Conclusions

Quasi-static and transient characteristics of AD 4AA63A4У3 were calculated using a mathematical model. Obtained electromagnetic and electromechanical characteristics for the modes of short circuit, ideal idling, nominal load and transient start-up mode. The analysis of the characteristics showed that the motor current in the short-circuit mode exceeds the reference current by 3.41 %. The electromagnetic moment is 11.7 % less than the reference value. In the nominal load mode, the angular velocity exceeds the reference value by 0.29 %, and the current is less by 1.19 %. The distribution of the magnetic induction, in the calculated modes, allows you to determine the saturation in the teeth and yoke of AD.

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