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INVESTIGATION OF ELECTROMAGNETIC PARAMETERS AND ELECTROMECHANICAL CHARACTERISTICS OF A DC MACHINE BASED ON THE FINITE ELEMENT METHOD

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The verification calculation of the serial machine of direct current (DCM) MUN-2 with a modified excitation system based on the finite element method (FEM), which allows to investigate the characteristics and electromagnetic parameters of DCM taking into account new design solutions in static, quasi-static and dynamic modes of operation. The finite element model of the DCM can be combined with the chain model of the power supply based on the joint *solution of the field and circuit equations, which makes it possible to investigate the characteristics of the engine in various modes when the anchor winding supplies signals of any shape.*

Based on the obtained results, the verification calculation of the DCM MUN-2 with a modified excitation system based on MSE allows the study of the characteristics and electromagnetic parameters of the DCM, considering new constructive solutions in dynamic modes of operation. The resulting DCM field model can be combined with the power source circuit model based on the joint solution of the field and circuit equations, which makes it possible to study the characteristics of the motor in different modes when feeding the armature winding with signals of any shape. The work established that the motor reaches the maximum rotation speed after 300 ms at a voltage of 120 V on the armature winding. At the same time, there is a surge in the starting current of the armature up to 2.0 A with subsequent stabilization at the level of 0.08 A. The starting torque reaches 1.2 Nm. The MUN-2 reaches the nominal rotation frequency at the nominal load, accompanied by an increase in the armature winding current to 0.7 A. During the operation of the motor, an electromotive force is induced in the armature winding, which, when the motor reaches the nominal rotation speed, stabilizes at the level of 20 V and has a peak character. Maxwell's system of electromagnetic fields and analytical and mathematical methods for partial differential equations are used to solve the problems. The finite element method is used to solve the differential equations of the magnetic field.

Key words: *finite element method, DC machine, magnetic induction, magnetic potential vector, electromechanical characteristics.*

Качура Олексій, Ніколенко Андрій, Кузнєцов Віталій, Саянов Олександр, Циплєнков Дмитро, Количев Сергій, Коваленко Віктор, Гурін Євген. ***Дослідження електромагнітних параметрів та електромеханічних характеристик машини постійного струму на основі методу кінцевих елементів***

Проведено перевірочний розрахунок серійної машини постійного струму (МПС) МУН-2 з модифікованою системою збудження на основі методу скінченних елементів, що дозволяє досліджувати характеристики та електромагнітні параметри МПС з урахуванням нових конструктивних рішень у статиці, квазістатичний і динамічний режими роботи. Скінченно-елементну модель можна поєднати з ланцюговою моделлю джерела живлення на основі спільного розв'язку рівнянь поля та схеми, що дає змогу досліджувати характеристики двигуна в різних режимах, коли обмотка якоря подає сигнали будь-якої форми.

На підставі отриманих результатів перевірочний розрахунок ДКМ МУН-2 з модифікованою системою збудження на основі МСЭ дозволяє досліджувати характеристики та електромагнітні параметри ДКМ, враховуючи нові конструктивні рішення в динамічних режимах роботи. Отриману модель поля DCM можна комбінувати з моделлю схеми джерела живлення на основі спільного розв'язку рівнянь поля та схеми, що дає можливість досліджувати характеристики двигуна в різних режимах за живлення обмотки якоря сигналами будь-якої форми. У роботі встановлено, що двигун досягає максимальної швидкості обертання через 300 мс за напруги 120В на обмотці якоря. При цьому спостерігається сплеск пускового струму якоря до 2,0А з подальшою стабілізацією на рівні 0,08А. Пусковий момент сягає 1,2Нм. МУН-2 досягає номінальної частоти обертання за номінального навантаження, що супроводжується збільшенням струму обмотки якоря до 0,7А. Під час роботи двигуна в обмотці якоря виникає електрорушійна сила, яка в разі досягнення двигуном номінальної швидкості обертання стабілізується на рівні 20В і має піковий характер. Для розв'язування задач використано систему електромагнітних полів Максвелла та аналітичні й математичні методи рівнянь у частинних похідних. Для розв'язування диференціальних рівнянь магнітного поля використовується метод скінченних елементів.

Ключові слова: *метод скінченних елементів, машина постійного струму, магнітна індукція, вектор магнітного потенціалу, електромеханічні характеристики.*

Introduction. In many cases, when it is necessary to regulate the performance of various mechanisms, asynchronous drives with frequency converters replace direct current electric drives [1–3]. Sometimes this circumstance is justified by the actual advantages of new technical solutions – reduction of electrical equipment dimensions, increased reliability and durability, standardization and unification of control systems [4; 5]. However, there are extensive areas where there is no alternative for dc electric drives: metallurgical equipment, ground transportation, precise positioning systems, instrument making, etc. In this regard, the task of researching the electromagnetic parameters of direct current machines in order to obtain electromechanical characteristics in dynamic modes of operation.

Important factors that must be considered when designing DCM are their reliability, cost-effectiveness, compliance with modern standards and technical requirements. Taking this into account, some methods [6] have been developed and applied, incorporating an analytical framework complemented by empirical relations and graphical dependencies obtained experimentally. As a rule, these methods are focused on general industrial series of machines with standard sizes and construction. Modification of the design and the use of new materials often cause challenges in designing. In this context, numerical methods become an important tool for DCM analysis, which allow to investigate the characteristics and parameters of DCM taking into account new design solutions in static, quasi-static and dynamic modes of operation. The finite element method (FEM) can be used to solve the challenges of DCM design.

Material and research results. Using FEM, the electromagnetic parameters and electromechanical characteristics of the mass-produced DCM MUN-2 (Figure 1), manufactured by the “Ostrovskiy Electric Machine Plant” (Ostrov city, Russia), was investigated in this study.

Considering the peculiarities of the local operation of the motor, the excitation system of the mass-produced machine has been changed from sequential Fig. 2a, on an independent one Fig. 2b, without any structural changes in the armature circuit. The motor armature winding scheme is shown in Fig. 3, its structural parameters – in Fig. 4, and the passport data are presented in Table 1.

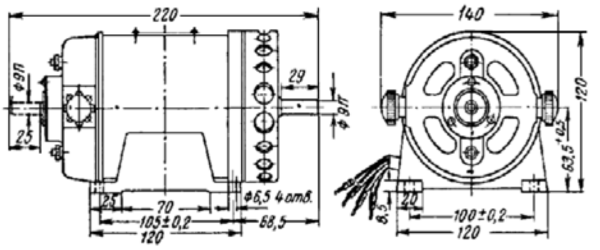

Fig. 1. Overall dimensions of mass-produced DCM MUN-2

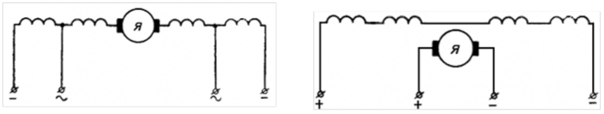
a b

Fig. 2. The excitation system of DCM MUN-2

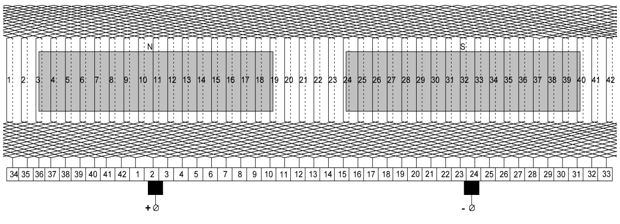

Fig. 3. Motor armature winding diagram

In order to perform the verification design, the DCM model is represented by field equations based on the FEM [9; 10], which allows to correctly describe the complex geometry of the motor taking into account the nonlinear properties of materials in both stationary and transient operating modes. The following assumptions were made during the development of the model:

1) the motor model is flat and considered in a rectangular coordinate system;

2) the current density in the winding is uniformly distributed over the entire cross-section;

3) structural details are simplified (technological grooves, fasteners and holes in them);

4) the armature winding and the excitation winding are powered by a constant voltage source of infinite power.

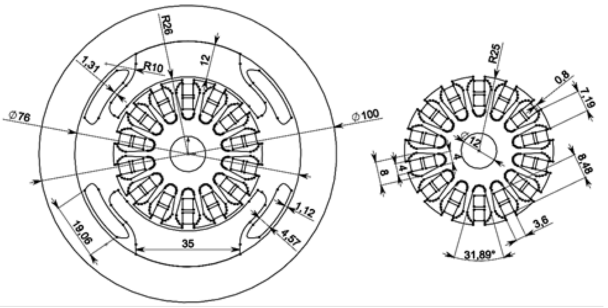

Fig. 4. Design parameters of DCM

Table 1

Technical data of DCM MUN-2 (according to the passport)

Type	MUN-2
Current Type	direct current
Excitation	sequential
Rated power, W	100
Rated voltage, V	220
Rated rotational speed, rpm	2200
Rated Torque, kg·cm	4.3
Rated current, A	0.9
Climatic modification	UHL (moderate and cold climate)
Location Category	4
Operating Mode	S1
Mass, kg	4.4

Based on the mathematical model considered in [7, 8], the system of equations describing DCM can be represented as follows:

$$\begin{cases} -\nabla\times\left(\nu_{\hat{a}}\nabla\times\vec{A}\right)=0 - \textit{air gap}; \\ -\nabla\times\left(\nu\,\nabla\times\vec{A}\right)=0 - \textit{the bed}; \\ -\nabla\times\left(\nu\,\nabla\times\vec{A}\right)=0 - \textit{the main poles}; \\ -\nabla\times\left(\nu_{\hat{a}}\nabla\times\vec{A}\right)=\dfrac{N_{\hat{a}}i_{\hat{a}}}{S} - \textit{pole winding}; \\ -\nabla\times\left(\nu\,\nabla\times\vec{A}\right)=-\upsilon\left(\dfrac{\partial A}{\partial x}-\dfrac{\partial A}{\partial y}\right) - \textit{armature core}; \\ -\nabla\times\left(\nu_{\hat{a}}\nabla\times\vec{A}\right)=-\upsilon\left(\dfrac{\partial A}{\partial x}-\dfrac{\partial A}{\partial y}\right)+\dfrac{N_a i_a}{S_a} - \textit{armature winding}; \\ -\nabla\times\left(\nu\,\nabla\times\vec{A}\right)=-\sigma\dfrac{\partial A}{\partial t}-\upsilon\left(\dfrac{\partial A}{\partial x}-\dfrac{\partial A}{\partial y}\right) - \textit{motor shaft}, \end{cases} \qquad (1)$$

where ∇ is the nabla operator; ν is the specific magnetic resistance of steel; $\vec{A}$ is the specific magnetic resistance; $\vec{A}$ is the vector magnetic potential; $i_{\hat{a}}$ is the current in the excitation winding; $i_{\grave{a}}$ is the current in the armature winding; $N_{\hat{a}}, S_{\hat{a}}$ are the number of turns and cross-sectional area of the excitation winding; $N_{\grave{a}}, S_{\grave{a}}$ are the number of turns and cross-sectional area of the armature winding; σ is the specific electrical conductivity of the material;
is the speed of rotation of the armature.

In a rectangular two-dimensional coordinate system, system (2) is transformed into the form [7]:

$$\begin{cases} \frac{\partial}{\partial x}\left(\nu_{\hat{a}}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{\hat{a}}\frac{\partial A}{\partial y}\right)=0-air\ gap; \\ \frac{\partial}{\partial x}\left(\nu\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial A}{\partial y}\right)=0-the\ bed; \\ \frac{\partial}{\partial x}\left(\nu\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial A}{\partial y}\right)=0-the\ main\ poles; \\ \frac{\partial}{\partial x}\left(\nu_{\hat{a}}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{\hat{a}}\frac{\partial A}{\partial y}\right)=\frac{N_{\hat{a}}i_{\hat{a}}}{S_{\hat{a}}}-pole\ winding; \\ \frac{\partial}{\partial x}\left(\nu\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial A}{\partial y}\right)=-\upsilon\left(\frac{\partial A}{\partial x}-\frac{\partial A}{\partial y}\right)-armature\ core; \\ \frac{\partial}{\partial x}\left(\nu_{\hat{a}}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{\hat{a}}\frac{\partial A}{\partial y}\right)=-\upsilon\left(\frac{\partial A}{\partial x}-\frac{\partial A}{\partial y}\right)+\frac{N_a i_a}{S_a}-armature; \\ \frac{\partial}{\partial x}\left(\nu\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial A}{\partial y}\right)=-\sigma\frac{\partial A}{\partial t}-\upsilon\left(\frac{\partial A}{\partial x}-\frac{\partial A}{\partial y}\right)-motor\ shaft. \end{cases} \qquad (2)$$

System (2) should be supplemented by voltage balance equations for the armature and excitation windings:

$$U_a = R_a \cdot i_a + \frac{dL_a(\gamma, i_a)\cdot i_a}{dt}; \qquad (3)$$

$$U_{\hat{a}} = R_{\hat{a}} \cdot i_{\hat{a}} + \frac{dL_{\hat{a}}(\gamma, i_{\hat{a}})\cdot i_{\hat{a}}}{dt}, \qquad (4)$$

where $U_a, U_{\hat{a}}$ are the supply voltages of the armature and excitation windings; $R_a, R_{\hat{a}}$, $L_a, L_{\hat{a}}$ are ohmic resistances and inductances of windings; $i_a, i_{\hat{a}}$ are currents of armature and excitation windings; γ is an angle of rotation of the armature relative to the winding of the poles.

Based on equation (3), a mathematical model of an electric circuit is implemented, simulating the operation of a brush-collector node together with an armature winding (Fig. 5).

To study electromechanical processes, the DCM mathematical model includes the basic equation of the dynamics of rotational motion

$$M - M_c = J\frac{d\omega}{dt}, \qquad (5)$$

where M is the magnitude of the electromagnetic torque; M_c is a static resistance torque on the shaft; J is the moment of inertia of the armature; $\vec{A}$ is an angular velocity of rotation of the armature.

The solution to equation (2) is reduced to solving the boundary value problem of Poisson and Laplace equations concerning the vector magnetic potential $\vec{A}$. Let us reduce the boundary value problem to the variational one and apply FEM for solving it [11, 12, 13]. In this case, system (2) is transformed into the matrix form:

$$[\mathrm{S}]\times\{\mathrm{A}\}+[\mathrm{N}]\times\frac{\partial\{A\}}{\partial \mathrm{t}}=[\mathrm{C}]\times\{\mathrm{i}\}, \qquad (6)$$

where $[S],[C],[N]$ are defined in [7].

Having calculated the values of the magnetic induction at each point of the DCM field, the electromagnetic torque acting on the armature can be calculated through the tension tensor [8]:

$$\bar{M} = \oint_S \left[\bar{r}\,\bar{T}_n\right] dS = \bar{q}_x M_x + \bar{q}_y M_y + \bar{q}_z M_z, \qquad (7)$$

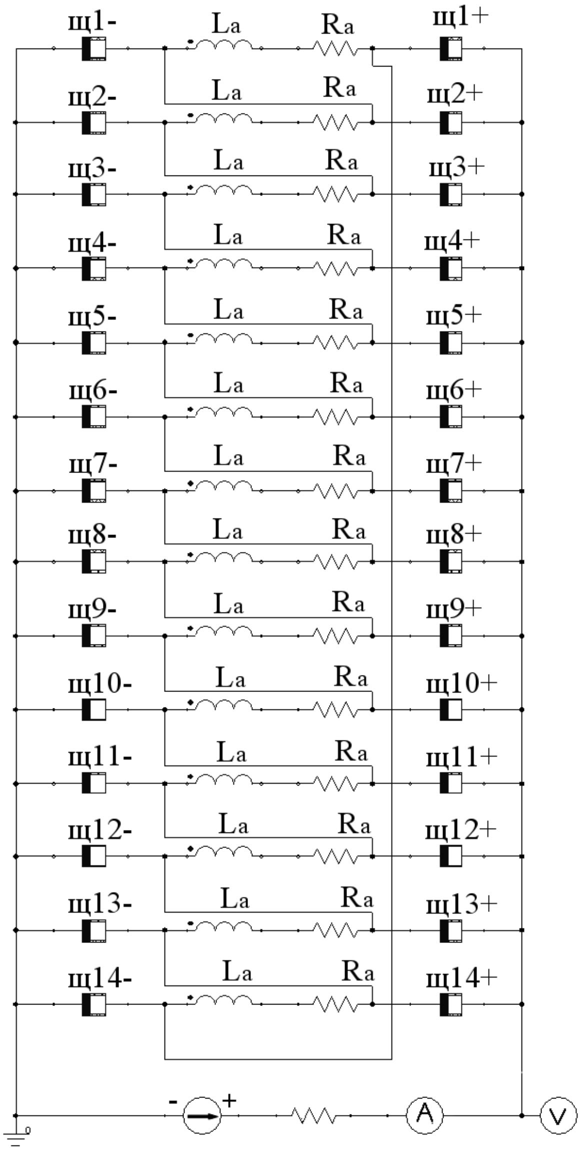

Fig. 5. Circuit diagram

where

$$M_x = \bar{q}_x\bar{M} = \oint_S \left(yT_{nz} - zT_{ny}\right)dS;$$

$$M_y = \bar{q}_y\bar{M} = \oint_S \left(zT_{nx} - xT_{nz}\right)dS;$$

$$M_z = \bar{q}_z\bar{M} = \oint_S \left(xT_{ny} - yT_{nx}\right)dS.$$

Here T_{nx}, T_{ny}, T_{nz} are the components of the stress tensor along the coordinate system axes.

Having combined the field problem (2) with the circuit equations (3), (4), we get a circuit-field model of a DC machine. We supplement the system (2)–(4) with the equation of mechanics (5).

2. Simulation Case

Based on the developed mathematical model, a verification calculation of the start-up mode of DCM MUN-2 with independent excitation without load, followed by loading up to the nominal torque, was performed. The calculation results include the following characteristics: armature rotation frequencies – Fig. 6; the electromagnetic torque of the motor – Fig. 7; armature winding branch current – Fig. 8; excitation winding current – Fig. 9; flux linkage of the armature winding branch – Fig. 10; EMF in the armature winding branch – Fig. 11. Fig. 12–15 show graphs of magnetic potential and magnetic induction distribution in the DCM cross-section at moments in time of 0.001 s and 0.2 s.

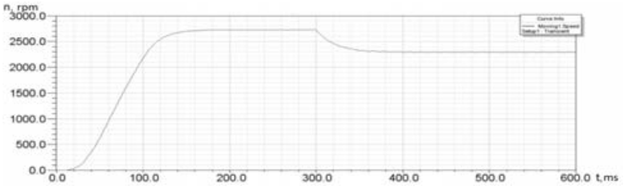

Fig. 6. DCM rotation frequency

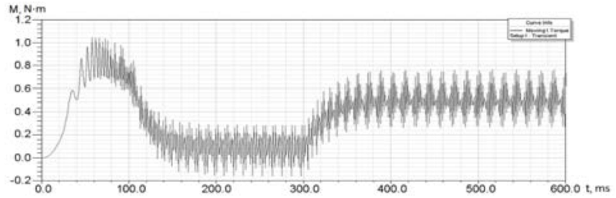

Fig. 7. Electromagnetic torque of the motor

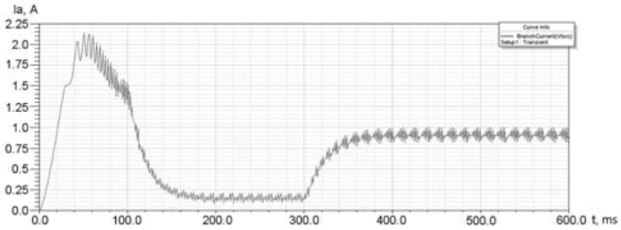

Fig. 8. Armature winding current

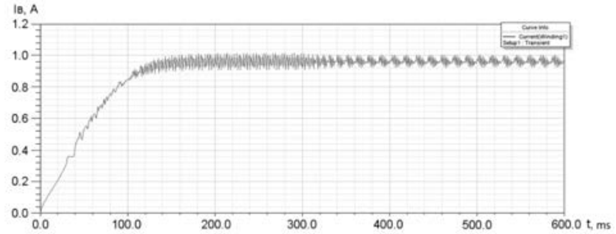

Fig. 9. Excitation winding current

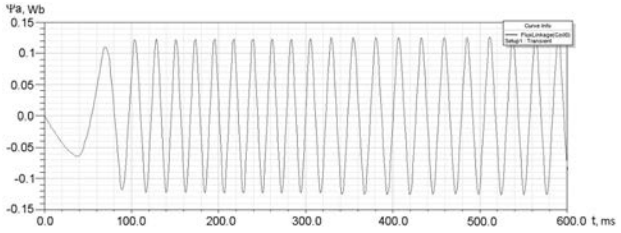

Fig. 10. Flux linkage in the armature winding section

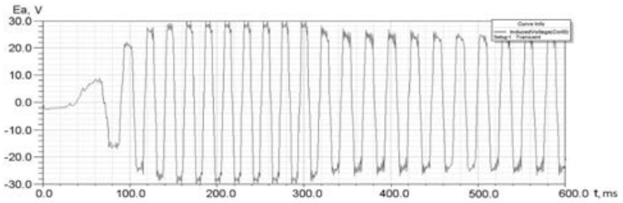

Fig. 11. Electromotive force induced in the armature winding section

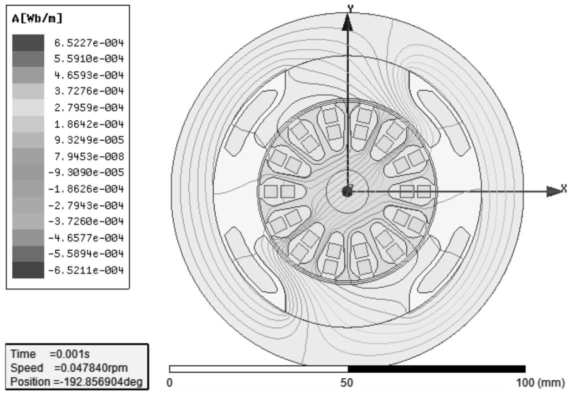

Fig. 12. Distribution of the vector magnetic potential of DCM at t = 0.001 s

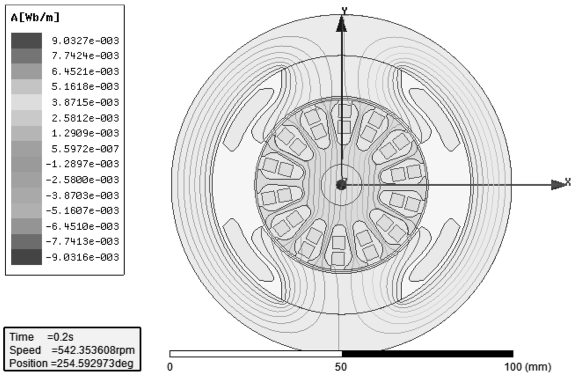

Fig. 13. Distribution of the vector magnetic potential of DCM at t = 0.21 s

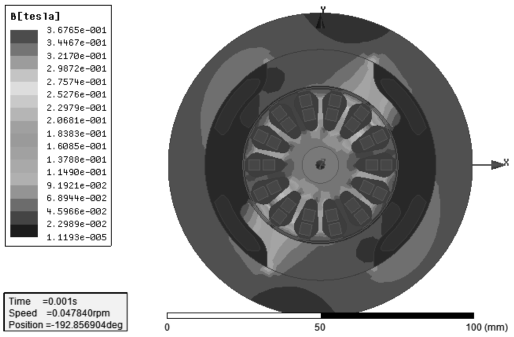

Fig. 14. Distribution of the magnetic induction of DCM at t = 0.001 s

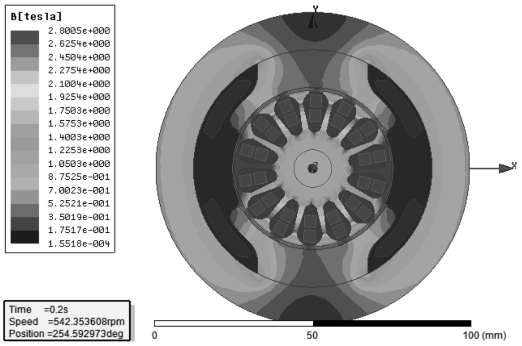

Fig. 15. Distribution of the magnetic induction of DCM at t = 0.2 s

3. Summary and Conclusion

On the basis of the obtained results, the following conclusions can be made: 1) a verification calculation of the DCM MUN-2 with a modified excitation system based on the FEM was performed. It allows to study the characteristics and electromagnetic parameters of the DCM taking into account new design solutions in dynamic modes of operation; 2) the field model of the DCM can be combined with the circuit model of the power source based on the joint solution of the field and circuit equations, which allows to study the characteristics of the motor in different modes when the armature winding is supplied with signals of any shape; 3) it has been determined that the motor reaches the maximum rotation speed after 300 ms with a voltage of 120 V on the armature winding. At the same time, there is a surge in the starting current of the armature up to 2.0 A with subsequent stabilization at the level of 0.08 A. The starting torque reaches 1.2 Nm; 4) when the nominal load is applied, the MUN-2 reaches the nominal rotation frequency, accompanied by an increase in the armature winding current up to 0.7 A; 5) during the operation of the motor, an electromotive force is induced in the armature winding, which, when the motor reaches the nominal speed of rotation, stabilizes at the level of 20 V and exhibits a peak character.

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3. Development of mathematical models of energy conversion processes in an induction motor supplied from an autonomous induction generator with parametric non-symmetry. *Eastern-European Journal of Enterprise Technologies* / V. Chenchevoi et al. 4 (8-112), pp. 67–82, DOI: 10.15587/1729-4061.2021.239146

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