DOI: 10.31319/2519-8106.1(50)2024.305056
UDC 621.313.323

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DESIGN OF A CIRCUIT-FIELD MODEL OF A CLOSED-LOOP ELECTRIC DRIVE SYSTEM BASED ON A SWITCHED RELUCTANCE MOTOR

РОЗРОБКА ЛАНЦЮГОВО-ПОЛЬОВОЇ МОДЕЛІ ЗАМКНЕНОЇ СИСТЕМИ ЕЛЕКТРОПРИВОДА НА БАЗІ ВЕНТИЛЬНОГО РЕАКТИВНОГО ДВИГУНА

The distribution of switched reluctance motors (SRM) is due to their specific properties: high reliability due to the absence of sliding contacts, precise positioning, wide range of regulation. These properties allow the use of SRM in various adjustable electric drives in conjunction with semiconductor control systems. The complexity of the study such systems is a correct representation of both, the control system and the motor, taking into account their mutual influence and energy exchange. In addition, as a rule, SRM have a rather specific design, which limits the use of classical methods for their calculation and causes the use of numerical methods. The paper presents a mathematical model of a *closed loop drive system on the rotor position and speed, based on the SRM. As a result of the unification of the SRM field model constructed on the basis of the Laplace and Poisson equations and the circuit model of the control system, a circuit-field mathematical model is obtained. The mathematical model takes into account the design features of the motor and allows to explore a drive system in dynamic modes of operation. An algorithm for switching power inverter keys for four phases of the SRM is developed. From the obtained values of magnetic induction and tension tensors the electromagnetic moment of the motor calculated. Electromagnetic and electromechanical parameters of the serial SRM-57-100-4 in the start-up mode obtained for the proposed model.*

***Keywords**: switched reluctance motor, closed loop electric drive system, control system, finite element method, dynamic operation mode, start mode.*

Електроприводи (ЕП) на базі вентильних реактивних двигунів (ВРД) є невід'ємною складовою високотехнологічного устаткування. Такі ЕП знаходять застосування у різноманітних пристроях: роботи, медичне устаткування, верстати з числовим програмним забезпеченням, комп'ютерна техніка. Поширення ВРД обумовлене їхніми властивостями: прецизійне позиціонування, широкий діапазон регулювання, висока надійність. У зв'язку з цим актуальним є дослідження характеристик і електромагнітних параметрів ВРД у складі керованого ЕП.

При створенні ЕП на базі ВРД виникає необхідність узгодження електромеханічної й схемотехнічної частин з урахуванням їх взаємного впливу. До основних труднощів, що виникають при побудові коректної моделі "система керування — ВРД", можна віднести: необхідність врахування взаємного енергообміну між двигуном і інвертором, складність конструкції ВРД, обумовлена зубчастою структурою статора й ротора, нелінійність властивостей матеріалів, несинусоїдальність індукції у повітряному проміжку між статором і ротором.

У роботі розглянута ланцюгово-польова математична модель ЕП на базі ВРД SRM-57-100-4, що знаходить застосування в апараті штучної вентиляції легень серії "Бриз-Т".

Для розрахунку характеристик і електромагнітних параметрів ВРД використано метод кінцевих елементів, що дозволяє коректно описати складну геометрію двигуна з урахуванням нелінійних властивостей матеріалів у стаціонарних і перехідних режимах роботи.

Метою роботи є створення ланцюгово-польової моделі замкненої системи ЕП на базі ВРД для дослідження перехідних режимів роботи з урахуванням енергообміну між інвертором і двигуном. Крім інвертора й ВРД електропривод включає систему керування, що складається з задатчика швидкості, датчика положення ротора, датчика швидкості, датчика струму обмотки статора, силового IGBT комутатора, системи керування комутатором, зворотного зв'язку за положенням ротора, зворотного зв'язку за швидкістю.

Об'єднавши польову модель ВРД із ланцюговою моделлю системи керування, отримано ланцюгово-польову модель замкненої системи електропривода зі зворотним зв'язком за швидкістю й положенням ротора. На основі розробленої математичної моделі виконано розрахунок режиму пуску ВРД до швидкості завдання. У результаті моделювання отримано залежності кута повороту ротора, електромагнітного моменту й струмів у фазних обмотках ВРД.

***Ключові слова**: вентильний реактивний двигун, замкнена система електроприводу, система керування, метод кінцевих елементів, динамічний режим, пусковий режим.*

Problem's Formulation

Electric drives (ED) based on switched reluctance motors are an integral part of high-tech equipment. These drives are used in a variety of devices: robots, medical equipment, CNC machines, copying and computer equipment. The spread of SRM is due to their properties: precision positioning, wide control range, high reliability. In this regard, it is imperative to study the electromagnetic parameters and characteristics of the SRM as part of controlled electric drive systems.

Analysis of recent research and publications

Recently, a lot of scientific literature has been devoted to the study of SRM [1—6].

In research [2] an electric drive system based on a SRM include an asymmetric four-phase power converter is considered. Based on mathematical modeling, the authors proposed a special converter control algorithm that provides improved performance compared to standard PI and fuzzy logic control. The reliability of the proposed algorithm is confirmed by the results of modeling in the MATLAB system by perturbation of mechanical parameters and external load.

Paper [4] is devoted to the study of SRM characteristics. The authors proposed a three — dimensional mathematical model of the motor with number of poles 6/4. Applying the Magnet CAD modeling environment, the value of SRM static moment calculated using finite element method (FEM). The model takes into account the end effects, scattering fields, the mutual inductance of the phases stator and rotor. Based on similar calculations for the two-dimensional model, a comparative analysis of SRM error parameters presented.

In [1], a parametric model of a switched reluctance generator (SRG) based on the finite element method is proposed. Using the ANSYS computing environment, the authors calculated the characteristics of a generator, obtained the transients of phase currents in the windings, analyzed the input and generated electric power. Based on the calculation of transients for a SRG with number of poles 8/6, the distribution curves of magnetic induction in the stator, rotor and in the poles are obtained, losses in steel for hysteresis and eddy currents are calculated. The authors found that the distribution curves of magnetic induction have a non-sinusoidal character, what affect for power losses. Based on the simulation results, in paper recommendations are formulated that can be taken into account when developing the SRG.

The paper [3] is devoted to the problem of the noise appearance in a SRM as a result of radial electromagnetic forces acting on the stator and rotor. In the article have shown that radial forces are the cause of vibration of the stator and rotor, what is the reason for the creation of a new design with enlarged poles. In addition, the proposed design of the SRM has an increased electromagnetic moment and reduced scattering fluxes, and the motor windings are placed in layers isolated from each other. The proposed SRM was investigated by the finite element method using the ANSYS Maxwell-3D computing environment, parametric analysis was performed in ANSYS-RMxprt.

The paper [5] presents an original approach to modeling a three-phase SRM with a pole ratio 6/4. Using the MATLAB/Simulink computing environment, the authors performed a numerical analysis of a SRM characteristics based on 2D nonlinear tables obtained as a result of flux linkage and static torque calculating. In addition, the hysteresis issues are considered, SRM current control algorithms are studied.

In research [6], a three-dimensional SRM model with a pole ratio of 8/6 is considered. Using the ANSYS, phase flow couplings, magnetic vector potential and magnetic flux density are calculated for various rotor positions and current values in the stator windings. Based on the simulation results, conclusions are made for the optimization of the design of the SRM and the materials used.

Formulation of the study purpose

When creating an electronic device based on SRM, there is a need to coordinate the electromechanical and schematic parts, taking into account their mutual influence. The main difficulties that arise when constructing a correct “control system — SRM” model are as follows: the need to take into account the mutual energy exchange between the motor and the electronic switch, distinct gear structure of the stator and rotor of the SRM, nonlinear properties of materials, non-sinusoidal induction in the air gap.

The paper considers a circuit-field mathematical model of electric drive based on the SRM-57-100-4 produced by “Elektrotekhnika” LLC (Mykolaiv city), used in the artificial lung ventilation apparatus “Breeze-T”. The magnetic system of the SRM is made with a stator to rotor pole ratio of 8/6, the stator and rotor packages are made of electrical steel grade 2211, the thickness of the plates is 0.5 mm. The active length of the stator and rotor is 28 mm. The design parameters of the motor are shown in Fig. 1, its technical data are presented in Tabl. 1.

Table 1. Technical data of the SRM

Rated torque, N·m	0.05
Rated power, W	21
Rated voltage, V	24
Maximum rotation speed, rpm	4500

Continue of the table 1

Maximum torque, N·m	0.1
Depth of regulation	1:500
Moment of inertia of the rotor, kg·m^2	0.0000055
Weight, kg	0.75
Cooling method	IC0040
Degree of protection	IP54

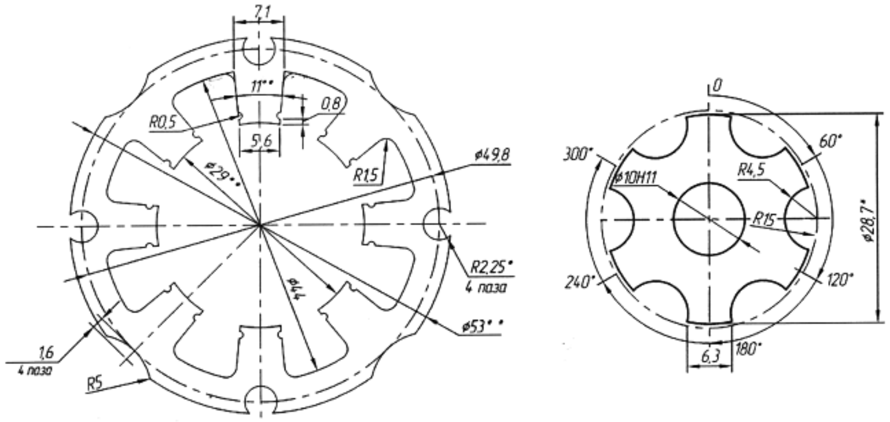

Fig. 1. SRM stator and rotor plates

To calculate the characteristics and electromagnetic parameters of the SRM, the finite element method was used, it allows us to correctly describe the complex geometry of the motor, taking into account the nonlinear properties of materials in stationary and transient operating modes. The following assumptions were made:

1) the frequency converter model is presented in the form of an ideal inverter, which is powered by a constant voltage source of infinite power;

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

3) the current density in the winding is distributed evenly over the entire cross-section;

4) small structural details (technological grooves, fastening recesses and holes) have been simplified.

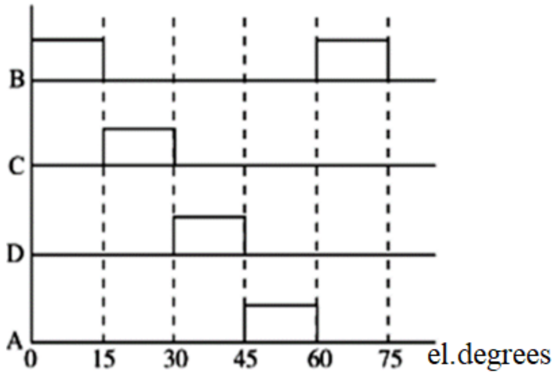

Fig. 2. Switching schedule of inverter switches

The purpose of the paper is to create a circuit-field model of a closed-loop ED system based on the SRM 57-100-4 in order to study transient operating modes taking into account the energy exchange between the switch and the motor.

Presenting main material

In a frequency converter, electromagnetic processes depend on a number of factors: the load connection, its nature, the valve switching algorithm, and the inverter circuit. Let's consider a model of a unipolar converter with a DC link. When switching inverter switches in unipolar mode, the voltage graph is a constant-sign pulse function with a switching period of 60 el. degrees (Fig. 2).

Mathematically, the impulse function can be described by equations of the following form:

$$u(u)=\begin{cases} +u_{nB}, 0<\theta<\dfrac{\pi}{12}; \\ +u_{nC}, \dfrac{\pi}{12}<\theta<\dfrac{2\pi}{12}; \\ +u_{nD}, \dfrac{2\pi}{12}<\theta<\dfrac{3\pi}{12}; \\ +u_{nA}, \dfrac{3\pi}{12}<\theta<\dfrac{4\pi}{12}; \end{cases} \tag{1}$$

where u_{nx} — voltage of the power source corresponding phase winding of the inverter; $\theta=\Omega\cdot t$ — time in angular units determined by the frequency Ω of the inverter output voltage.

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

$$\begin{cases} -\nabla\times\left(\nu\nabla\times\vec{A}\right)=0-\text{air gap}; \\ -\nabla\times\left(\nu\nabla\times\vec{A}\right)=0-\text{stator}; \\ -\nabla\times\left(\nu\nabla\times\vec{A}\right)=\dfrac{N_w i_x}{S_w}-\text{stator groove}; \\ -\nabla\times\left(\nu\nabla\times\vec{A}\right)=-\upsilon\left(\dfrac{\partial A}{\partial x}-\dfrac{\partial A}{\partial y}\right)-\text{rotor}; \\ -\nabla\times\left(\nu\nabla\times\vec{A}\right)=-\sigma\dfrac{\partial A}{\partial t}-\upsilon\left(\dfrac{\partial A}{\partial x}-\dfrac{\partial A}{\partial y}\right)-\text{shaft}, \end{cases} \tag{2}$$

where ∇ — del operator; ν — specific magnetic resistance of steel; $\vec{A}$ — vector magnetic potential; x — index of the corresponding phase winding; i — current in the phase winding; N_w, S_w — number of turns and cross-section area of the phase winding; σ — specific electrical conductivity of the material; υ — rotor rotation speed.

In a rectangular two-dimensional coordinate system, equations (2) are transformed to the form:

$$\begin{cases} \dfrac{\partial}{\partial x}\left(\nu\dfrac{\partial A}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\nu\dfrac{\partial A}{\partial y}\right)=0-\text{air gap}; \\ \dfrac{\partial}{\partial x}\left(\nu\dfrac{\partial A}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\nu\dfrac{\partial A}{\partial y}\right)=0-\text{stator}; \\ \dfrac{\partial}{\partial x}\left(\nu\dfrac{\partial A}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\nu\dfrac{\partial A}{\partial y}\right)=\dfrac{N_w\cdot i_x}{S_w}-\text{stator groove}; \\ \dfrac{\partial}{\partial x}\left(\nu\dfrac{\partial A}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\nu\dfrac{\partial A}{\partial y}\right)=-\upsilon\left(\dfrac{\partial A}{\partial x}-\dfrac{\partial A}{\partial y}\right)-\text{rotor}; \\ \dfrac{\partial}{\partial x}\left(\nu\dfrac{\partial A}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\nu\dfrac{\partial A}{\partial y}\right)=-\sigma\dfrac{\partial A}{\partial t}-\upsilon\left(\dfrac{\partial A}{\partial x}-\dfrac{\partial A}{\partial y}\right)-\text{shaft}. \end{cases} \tag{3}$$

System (3) must be supplemented with voltage equilibrium equations for each phase winding

$$\{u_x\}=[r_x]\{i_x\}+\frac{N_w l}{S_w}\left\{\int\limits_{S_w}\frac{\partial A}{\partial t}dS_w\right\}+L_{л}\frac{d\{i_x\}}{dt} \tag{4}$$

and the basic equation of the dynamics of rotational motion

$$M\text{-}M_c=J\frac{dw}{dt}, \tag{5}$$

where $\{u_x\}$ is the vector of phase voltages; $[r_x]$ is matrix of ohmic resistances of the phase winding of the motor; $\{i_x\}$ is a vector of currents in phase windings; $L_л$ is an inductance of the frontal parts; l is a length of the conductor; M is the magnitude of the electromagnetic moment; M_c is a static moment of resistance on the shaft; J is a moment of inertia of the rotor; $щ$ is an angular speed of rotation of the rotor.

The problem of solving system (3) is reduced to the boundary value problem of solving the Poisson's equations with respect to the vector magnetic potential $\vec{\mathrm{A}}$. Let us reduce the boundary value problem to a variational one and apply FEM. In this case, system (3) is transformed to the form

$$\mathbf{S}\times\mathbf{A}+\mathbf{N}\times\frac{\partial\mathbf{A}}{\partial t}=\mathbf{C}\times i,$$

where $\mathbf{S}$, $\mathbf{C}$, $\mathbf{N}$ are defined in [7].

Having determined the values of magnetic induction at each point in the field of the SRM region, the electromagnetic torque acting on the rotor can be calculated through stress tensors:

$$\overline{\mathrm{M}}=\oint_S[\bar{\mathrm{r}}\,\overline{\mathrm{T}}_\mathrm{n}]dS=\bar{\mathrm{q}}_\mathrm{x}\mathrm{M}_\mathrm{x}+\bar{\mathrm{q}}_\mathrm{y}\mathrm{M}_\mathrm{y}+\bar{\mathrm{q}}_\mathrm{z}\mathrm{M}_\mathrm{z},$$

where

$$\mathrm{M}_\mathrm{x}=\bar{\mathrm{q}}_\mathrm{x}\overline{\mathrm{M}}=\oint_S\left(\mathrm{yT}_\mathrm{nz}-\mathrm{zT}_\mathrm{ny}\right)dS;$$

$$\mathrm{M}_\mathrm{y}=\bar{\mathrm{q}}_\mathrm{y}\overline{\mathrm{M}}=\oint_S\left(\mathrm{zT}_\mathrm{nx}-\mathrm{xT}_\mathrm{nz}\right)dS;$$

$$\mathrm{M}_\mathrm{z}=\bar{\mathrm{q}}_\mathrm{z}\overline{\mathrm{M}}=\oint_S\left(\mathrm{xT}_\mathrm{ny}-\mathrm{yT}_\mathrm{nx}\right)dS.$$

Here T_nx, T_ny, T_nz are the components of the tension tensor along the axes of the coordinate system.

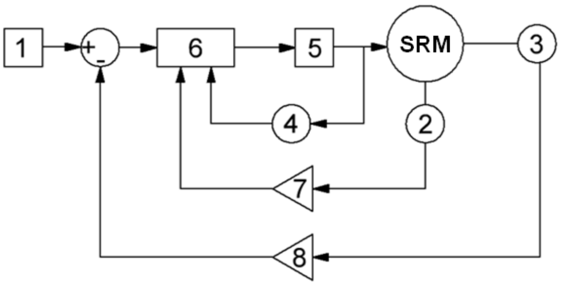

Fig. 3. SRM control system

In addition to the voltage inverter and the SRM, the considered electric drive includes a control system (Fig. 3), consisting of: 1) speed controller; 2) rotor position sensor; 3) speed sensor; 4) stator winding current sensor; 5) power IGBT switch; 6) switch control systems; 7) feedback on rotor position; 8) speed feedback.

By combining the field model of the SRM with the chain model of the control system (Fig. 4), we will obtain a chain-field model of a closed-loop electric drive system with feedback on the speed and position of the rotor. Receiving information about the current position of the rotor and its speed based on the readings of the corresponding sensors, the control system generates constant-sign pulses with a phase sequence *B-C-D-A* with a displacement of 15 el. degrees entering the power inverter. The inverter connects the corresponding phase winding of the SRM to the +24V direct current voltage source.

Based on the developed mathematical model, the startup mode of the SRM 57-100-4 was calculated up to a set speed of 157 rad/sec. As a result of the simulation, the dependences of the rotor rotation angle (Fig. 5), electromagnetic torque (Fig. 6), and currents in the phase windings (7) were obtained. Fig. 8 shows graphs of the distribution of magnetic induction in the cross-section of the SRM for different moments of time.

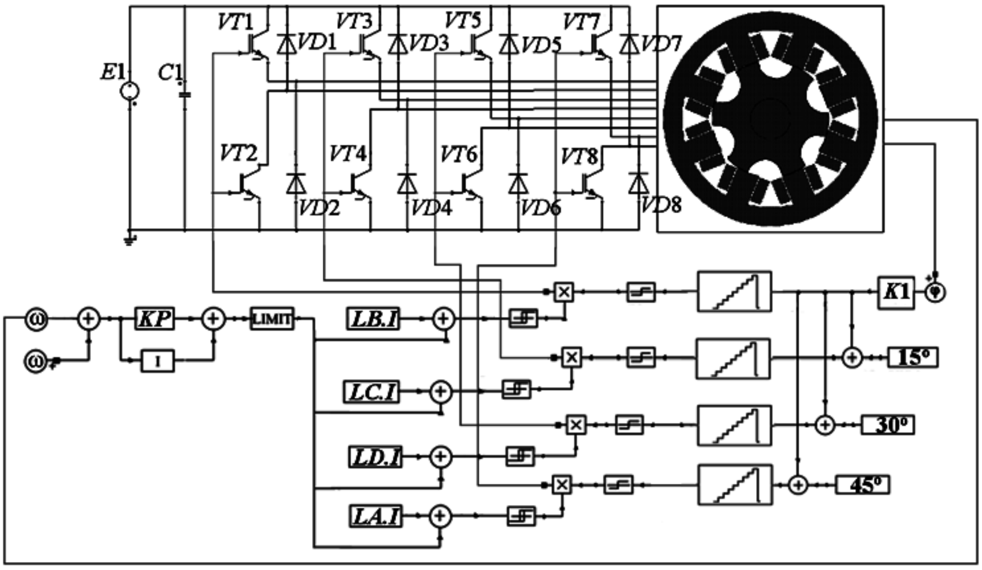

Fig. 4. Circuit diagram of a closed-loop drive system based on a SRM

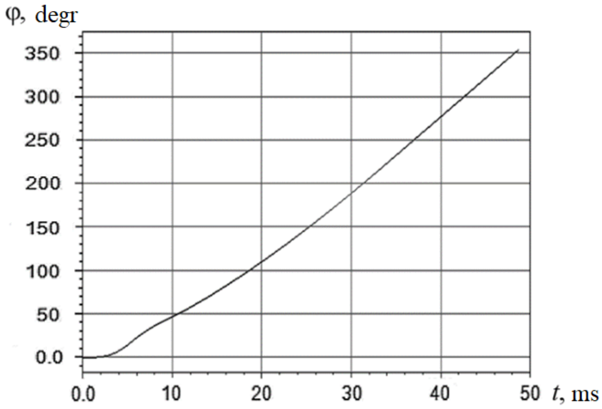

Fig. 5. Dependence of the rotation angle of the SRM rotor

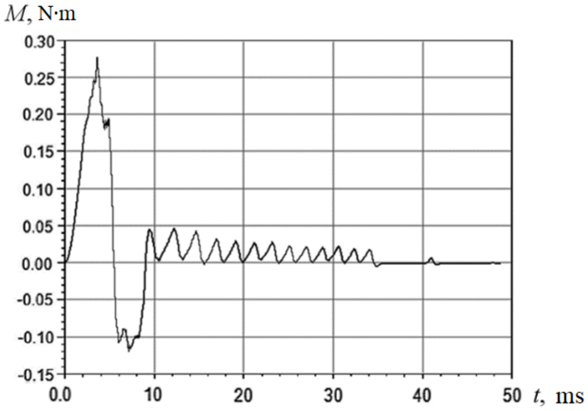

Fig. 6. Graph of the transient process of the electromagnetic torque

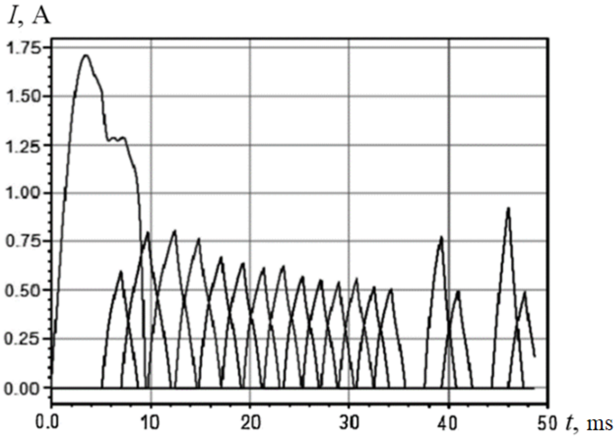

Fig. 7. Graphs of current transient process in the phase windings of the SRM

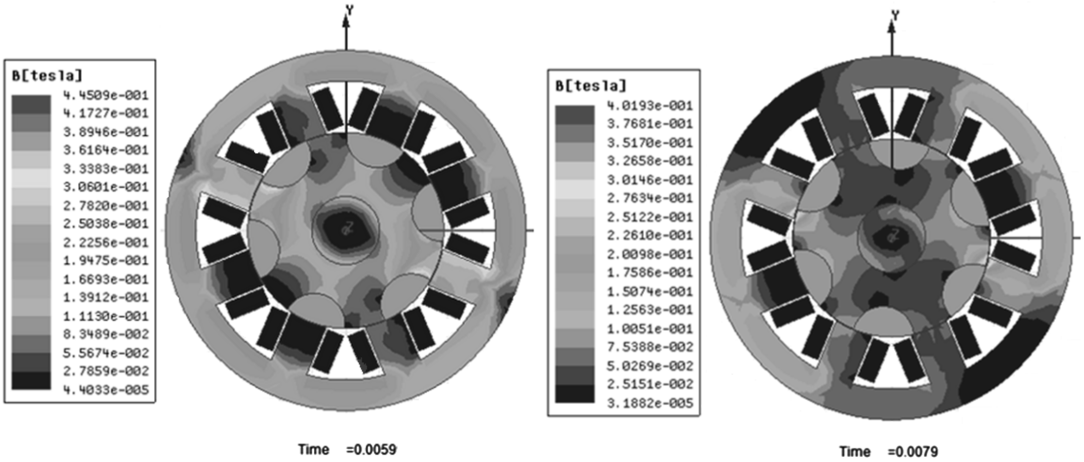

Fig. 8. Distribution of magnetic flux density in the SRM section

Conclusions

Based on the results obtained, the following conclusions can be made: 1) the finite element model of the SRM can be combined with the chain model of the power switch and its control system, thereby forming a closed electric drive system with feedback on the rotor position and the speed of the SRM; 2) it follows from Fig. 5—7, that the use of a closed ED system makes it possible to ensure an almost linear change in the rotor position. In this case, a fivefold jump in the starting torque is observed over a time period of 10 ms. Further acceleration of the motor is accompanied by a decrease in the starting torque with its subsequent stabilization at the level of 0.025—0.05 N·m; 3) it is found that the motor reaches the required reference speed in 35 ms. In this case, the starting current increases to 1.7 A with a subsequent decrease to 0.5 A; 4) over a period of time of 36—38 ms and 42—44 ms, a decrease in current and electromagnetic torque is observed to 0 A and 0 N· m, respectively, which is explained by the switching off of certain phase windings of the motor by the inverter based on signals from the control system when the rotor speed of the SRM is increased above given.

References

[1] Ganji B., Heidarian M., Faiz J. (2015). Modeling and analysis of switched reluctance generator using finite element method. Ain Shams Engineering Journal, Vol. 6, p. 85–93.

[2] Ghada A., Aziz A., Amin M. (2018). High-precision speed control of four-phase switched reluctance motor fed from asymmetric power converter. Journal of Electrical Systems and Information Technology, Vol. 5, p. 300–311.

[3] Özüpak Y. (2022). Design and analysis of switched reluctance motor with FEM based Ansys-Maxwell. Manas Journal of Engineering, Vol. 10, Issue 2, p. 159-164.

[4] Torkaman H, Afjei E. (2008). Comprehensive Study of 2-D and 3-D Finite Element Analysis of a Switched Reluctance Motor. Journal of Applied Sciences, Vol. 8, Issue 15, p. 2758-2763.

[5] Arif A., Guettaf A., Megherbi A.C., Benramache S., Habane F.B. (2014). Electromagnetic modeling and control of switched reluctance motor using finite elements. Frontiers in Energy, Vol. 8(3), p. 355-363.

[6] Sree D.K., Jebaseeli A.E. (2016). Electromagnetic Analysis of Switched Reluctance Motor using Finite Element Method. Indian Journal of Science and Technology, Vol 9(34).

[7] Kachura A.V., & S'yanov A.M. (2015). Razrabotka matematicheskoy modeli ventilnogo reaktivnogo dvigatelya na osnove metoda konechnyih elementov dlya sistem tochnogo pozitsionirovaniya [Development of a mathematical model of a switched reluctance motor based on the finite element method for accurate positioning systems]. *ZbIrnik naukovih prats DnIprodzerzhinskogo derzhavnogo tehnIchnogo unIversitetu – Collection of scientific papers of Dneprodzerzhinsky State Technical University, 1(1),* 87-93.

Список використаної літератури

1. Ganji B., Heidarian M., Faiz J. Modeling and analysis of switched reluctance generator using finite element method. Ain Shams Engineering Journal. 2015. Vol. 6, p. 85–93
2. Ghada A., Aziz A., Amin M. High-precision speed control of four-phase switched reluctance motor fed from asymmetric power converter. Journal of Electrical Systems and Information Technology. 2018. Vol. 5, p. 300–311.
3. Özüpak Y. Design and analysis of switched reluctance motor with FEM based Ansys-Maxwell. Manas Journal of Engineering. 2022. Vol. 10, Issue 2, p. 159–64.
4. Torkaman H, Afjei E. Comprehensive Study of 2-D and 3-D Finite Element Analysis of a Switched Reluctance Motor. Journal of Applied Sciences. 2008. Vol. 8, Issue 15, p. 2758–2763.
5. Arif A., Guettaf A., Megherbi A.C., Benramache S., Habane F.B. Electromagnetic modeling and control of switched reluctance motor using finite elements. Frontiers in Energy. 2014. Vol. 8(3), p. 355–363.
6. Sree D.K., Jebaseeli A.E. Electromagnetic Analysis of Switched Reluctance Motor using Finite Element Method. Indian Journal of Science and Technology. 2016. Vol 9(34).
7. Качура А.В., Съянов А.М. Разработка математической модели вентильного реактивного двигателя на основе метода конечных элементов для систем точного позиционирования. Збірник наукових праць Дніпродзержинського державного технічного університету. Технічні науки. 2015. Вип. 1. С. 87–93.

Надійшла до редколегії 06.12.2023