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The Nature of Electromagnetic Processes in Electric Traction Machines NB-514

Sardor Nuriddinov[a], Maftuna Tosheva[b]

[a] *Associate Professor, Almalyk branch of the Tashkent State Technical University named after Islam Karimov, Tashkent, Uzbekistan*

[b] *PhD Student, "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University, Tashkent, Uzbekistan*

a r t i c l e i n f o

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a b s t r a c t

In solving the problem of determining the magnetic field, the following assumptions were made in the article: – the calculation takes into account the flat transverse magnetic fields of the studied electric motor model; - there is no saturation of the magnetic circuit, the magnetomotive force and magnetic fluxes correspond to the linear part of the magnetic characteristic of electric motors; - the magnetic field does not go beyond the model framework.

The results of some calculations of the magnetic field are presented in the form of the distribution of the vector magnetic potential and equipotential lines of magnetic field induction of 6 TEM models. A synthesis of the obtained values of the reduced magnetic field parameters is carried out.

1. INTRODUCTION

A magnetic field is one of the four force fields that exist in nature. It acts on moving electric charges and on bodies that have a magnetic moment regardless of their motion. Physical bodies around which a magnetic field is formed are magnetized bodies, current-carrying conductors, and moving electrically charged bodies. In all cases, a magnetic field arises due to the movement of tiny charged particles and as a result of these particles having their own magnetic moment.

One of the graphical ways to represent a magnetic field is to construct a magnetic field picture – a representation of magnetic lines of force or equipotential lines of vector magnetic potential that characterize this field. At each point of such a line, the magnetic induction vector B is located along the tangent, [2,3]. Figure 1. shows the equipotential lines of vector magnetic potential of a two-dimensional TED model.

In a general consideration of this process, the magnetic field is one of the sides of the electromagnetic field, which is caused by the electric charges of moving particles and bodies and the change in the electric field. In addition to the construction, the magnetic field itself is revealed by the force it exerts on the charged particles moving relative to it. The field of the magnetic induction vector has no divergence (there are no sources or drains, the lines of magnetic induction are continuous and form closed loops), [1,4].

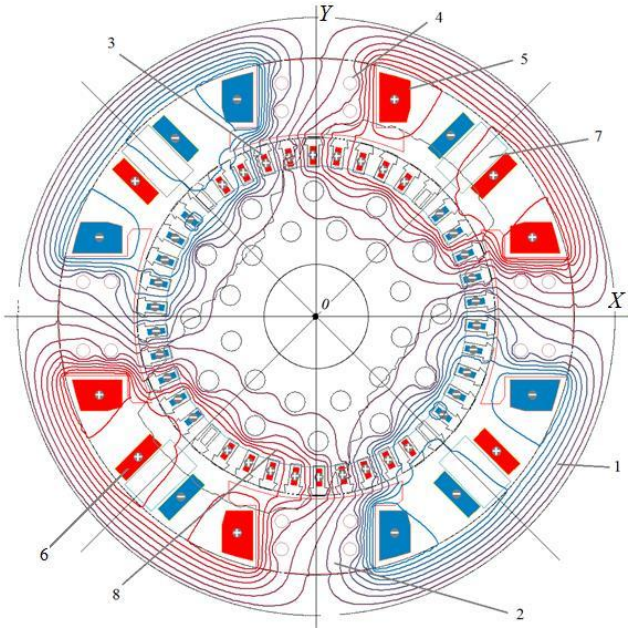


Figure 1. – Equipotential lines of the vector magnetic potential of a two-dimensional model of a TED 1 – frame; 2 – main pole core; 3 – armature winding; 4 – longitudinal channel; 5 – main pole winding; 6 – additional pole winding; 7 – additional pole core; 8 – armature.

* Corresponding author. boboyarovich@bk.ru (S.Nuriddinov) Scopus ID: 57224735693
E-mail addresses: m_tosheva@tiiame.uz (M.Tosheva).

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2. RESULTS

The widespread use of electromagnetic processes for electromechanical energy conversion, its study, construction and calculations are necessary and important primarily because a significantly higher concentration of energy is achieved in a magnetic field than in an electric field [5].

In electromechanical systems, it provides greater potential for use in human economic activity. Due to this property, almost all electric energy according to [3] (up to 20,000 kWh per person per year) is generated by electromechanical energy converters - generators (operating at thermal, nuclear, wind and hydroelectric power plants), and about 60-70% of the energy obtained is converted into mechanical energy using reverse electromechanical energy converters - electric motors.

The interaction of substances, physical bodies and electric currents in a magnetic field occurs due to the presence of magnetic dipoles, which can be calculated and shown in the form of magnetic (Faraday) tubes or a magnetic circuit. Many prominent scientists studied and described electromagnetic, magnetic and electric fields: M. Faraday, E. Lenz, H. Oersted, B. Jacobi, D. Maxwell, D. Henry and others, [9, 19, 20].

The purpose of the study is to describe the selection of TEM parameters based on a criterial equation based on the characteristics of magnetic field pulsations in an electric motor. The calculation is based on the numerical solution of the Poisson equation as applied to the vector magnetic potential - A, [5, 4, 6].

$$\nabla 2A = -\mu a\bar{\delta}, \qquad (1)$$

where μa is the absolute magnetic permeability, H/m;

$\bar{\delta}$ is the current density, A/m2.

Definition of magnetic field induction.

$$B = rotA = \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix}, \qquad (2)$$

where i, j, k are unit unit vectors along the coordinate axes x, y, z, respectively.

The cross-section of the TEM passing through the middle of the anchor can be represented through one component of the vector magnetic potential – the z axis, Az. In this regard, the following assumptions are made according to [7]:

Ax = Ay = 0 and Az = A.

Therefore, the formula for determining the vector magnetic potential is written in the following form:

$$\nabla^2 A = \frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} \qquad (3)$$

It is necessary to study the magnetic field induction, in connection with which the most significant element in the calculations is the determination of the magnetic field in a non-stationary mode with changing boundary conditions, i.e. in the mode in which the motor anchor rotates. In addition, in the calculations to determine the distribution pattern of the equipotential lines of the vector magnetic potential, the following factors must be taken into account:

– changes in the relative position of the anchor relative to the stationary parts of the magnetic system;

– displacements of the commutation zone relative to the neutral;

– asymmetry of air gaps between the structural elements of the electric motor.

In addition, it is necessary to take into account the effect of eddy currents on the magnetic field parameters. In this regard, the following assumption was made. If a non-stationary magnetic field is present in an element of the electric motor structure, which causes eddy currents to appear. Then, based on the 1st Maxwell equation, the magnetic field strength rotor is determined by the dependence:

$$rot\bar{H} = \bar{\delta} + \varepsilon\frac{\partial \bar{E}}{\partial t}, \qquad (4)$$

where: $\bar{\delta}$ – eddy current density, A/m2;

($\bar{H}$)– magnetic field strength, A/m;

ε – permittivity of the element under consideration;

$\bar{E}$ – electric field strength, N/C.

Substituting the values of magnetic permeability μ for the terms of this equation, and taking into account that $\bar{B} = \mu \cdot \bar{H}$, we obtain an expression of the form:

$$rot\bar{H} = \overline{\mu\delta} + \mu\varepsilon\frac{\partial \bar{E}}{\partial t}, \qquad (5)$$

Since $\bar{B} = rotA$, expression (5) is written in the following form:

$$rot\ rotA = \overline{\mu\delta} + \mu\varepsilon\frac{\partial \bar{E}}{\partial t}, \qquad (6)$$

The use of Maxwell's 2nd equation allows us to remove the electric field strength $\bar{E}$ from expression (6).

$$rot\bar{E} = -\frac{\partial \bar{B}}{\partial t} \qquad (7)$$

Taking this into account:

$$rot\bar{E} = -\frac{\partial}{\partial t}\ rot(A) = rot(-\frac{\partial A}{\partial t}) \qquad (8)$$

In further research, it is worth noting the fact that in an electrostatic field, the vector $\bar{E}$ is determined by the gradient of the scalar potential U and, in particular, by the increment of the vector magnetic potential.

$$\bar{E} = -\frac{\partial A}{\partial t} - grad\ U \qquad (9)$$

Due to the fact that:

$$rot\ rot(A) = divA - \nabla^2 A \qquad (10)$$

Then expression (9) can be written in the following form:

$$grad\ divA - \nabla^2 A = \mu\delta + \mu\varepsilon\frac{\partial \bar{E}}{\partial t}\mu\delta - \mu\varepsilon\left[\frac{\partial^2 A}{\partial t^2} - grad(\frac{\partial U}{\partial t})\right] \qquad (11)$$

Besides, if we take into account that

$$grad\ divA = \mu\varepsilon grad(\frac{\partial U}{\partial t}) \qquad (12)$$

That expression (11) can be simplified, and the equation of the magnetic field created by eddy currents takes the following form:

$$\nabla^2 A = -\mu\delta = \mu\varepsilon\frac{\partial^2 A}{\partial t^2} \qquad (13)$$

Since displacement currents are neglected in relation to ferromagnetic materials ($\mu\varepsilon\frac{\partial^2 A}{\partial t^2}$), the expression is written in the form of notation (1). To obtain the final form of the magnetic field equation, the following equalities must be taken into account:

$$\delta = \gamma\bar{E}. \qquad (14)$$

Taking into account the expression (1.9):

$$\delta = -\gamma\frac{\partial A}{\partial t} \qquad (15)$$

To obtain the final form of recording the magnetic field in the active section of the electric motor, it is necessary to take into account the fact that the magnetic field is generated not only by eddy currents, but also by currents flowing in the excitation windings. In this regard, the final equation of the magnetic field is written in the following form.

$$\nabla^2 A = \frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = \mu(x,y)\left[\gamma(x,y)\frac{\partial A}{\partial t} - \delta(x,y)\right] \qquad (1.16)$$

where μ(x,y) is the magnetic permeability, H/m;

γ(x,y) is the electrical conductivity, Sm

To determine the harmonic function satisfying the Laplace equation and having specified values at the boundaries of the region under consideration, it is necessary to solve the Dirichlet problem [7,9]. As is known and as has already been said, the magnetic circuit of an electric machine forms a closed loop. Which consists of piecewise homogeneous parts located in different environments. Figure 1.2 shows an example of the distribution of the magnetic field in the TEM model in the form of magnetic tubes.

As is known, the electromagnetic process - the transformation of electromagnetic energy into mechanical energy and back lies at the heart of all electric machines [3, 8]. Calculating the magnetic field in electric machines makes it possible to determine the electromotive and mechanical forces, and thereby find the required design option. Carrying out calculations of this kind requires an understanding of the physical processes that occur in magnetic materials.

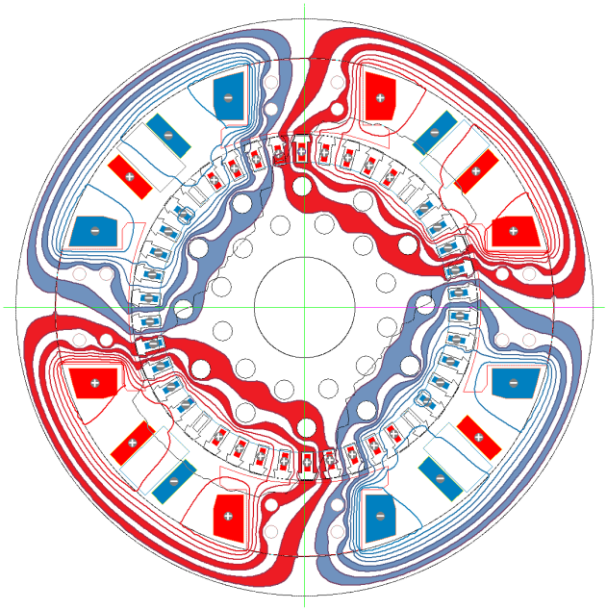


Figure 2 – Distribution of the magnetic field in the form of tubes for a two-dimensional model of a DC TEM

The following methods for calculating electromagnetic fields are known today:

– analytical: Fourier transforms, conformal mappings (shown in Govorkov, [4]);

– engineering: method for solving partial differential equations, solving electromagnetic field equations in integral form;

– numerical methods: integral method, method for determining the conductivity of toothed contours, finite difference method, finite element method;

– methods for modeling magnetic fields: using conductive paper, electrolytic baths, grid models.

Calculating the magnetic field for electromechanical energy converters is a key element at the design stage of TEM, this is indicated, in particular, in [3,1]. It is especially important to use modern calculation methods and mathematical modeling. An analysis of literary sources allowed us to conclude that the most applicable means for calculating the magnetic field at present are methods for numerically solving equation (16).

The grid is constructed using the finite element method on a model of the object under study. This method has its positive aspects: it is possible to construct a denser grid in places of predicted sharp changes in the value under study for a more accurate calculation, and to construct a wider grid in predicted places with a smaller gradient of values, with a significant distance of the grid nodes relative to each other.

The disadvantages include the need to link nodes at the boundaries of the sub-areas under study, i.e. to make them common, despite the fact that the sub-areas under study themselves may differ significantly relative to each other; after each calculation, it is necessary to rebuild the finite element grid, if necessary, since there is a risk of increasing the calculation error using a grid constructed on the area under study in a unit of time preceding the calculation, while significant human and machine resources are expended.

Using the finite difference method, it is possible to determine the magnetic field values with the required accuracy, taking into account the boundary conditions, the geometry of the structures and the nature of the initial stress state [2, 7].

The advantage of the finite difference method is the simplicity of the algorithm used, which is well suited for calculations using special programs on a PC. The essence of the finite difference method is described in more detail in the following literature sources. The solutions obtained using the finite difference method are approximate, while it is possible to obtain any degree of accuracy by changing the scaling of the models.

The disadvantage is the high order of the systems of algebraic equations, which, however, is leveled out when using electronic computing equipment. The finite difference method is also characterized by difficulties in taking into account mixed boundary conditions, considering multi-connected regions and junctions of regions described by various differential equations.

Modern computing equipment has sufficient and necessary computing power to solve a large problem with a large number of differential equations. It is possible, by changing the scale, to bring the number of nodes in the model to tens and hundreds of thousands, in addition, it is possible to carry out sequential calculations, i.e. iterations tens of thousands of times - all this increases the accuracy of the obtained data many times.

3. CONCLUSION

To conduct the study, the author suggests using the FELD (field) program for PC, which is designed to solve problems related to magnetic, electric, electrostatic and thermal fields, as applied to electric machines. The program works in the Assembler environment as a Windows application, can be used as a library (*.dll) together with Pascal, Delphi, Excel, etc. In addition, FELD has an interface that allows you to build models, set various parameters of the environment, boundary conditions, carry out calculations, set the movements of elements and display the results. A graphical representation of the program interface is presented in Appendix 4 in Figure P4.1. The accuracy of numerical methods for solving differential equations of the form (1.16) also depends on the methods of cross-section quantization [16], this is especially important for boundary conditions where a sudden change in magnetic permeability and refraction of magnetic lines of force are possible, for example, at the boundary of an air gap in an electric motor. The minimum possible step when quantizing a model cross-section on a PC monitor is 1 pixel, the number of grid nodes in this case reaches 1*106.

Assumptions made in the work when solving the problem of determining the magnetic field:

– flat transverse magnetic fields of the studied electric motor model are taken for the calculation; – there is no saturation of the magnetic circuit, the magnetomotive force and magnetic fluxes correspond to the linear part of the magnetic characteristic of electric motors; – the magnetic field does not extend beyond the boundaries of the model frame.

The results of some calculations of the magnetic field in the form of the distribution of equipotential lines of the vector magnetic potential and the magnetic field induction of 6 TEM models are shown in Section 3 in Figures 3.1 – 3.6. Based on the constructed graphs, a synthesis of the obtained values of the magnetic field parameters was carried out, presented in Section 4. In this case, the value of the magnetic field induction along the normal and the values of the vector magnetic potential were taken into account, the tangential component of the induction was not taken into account due to small values relative to the magnetic field induction.

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