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MODELING OF THE EXTERNAL MAGNETIC FIELD OF ELECTRIC MACHINES

Abstract. Powerful electric machines – such as electric generators, electric motors generate a magnetic field of great tension. These fields negatively effect on personnel and can to violate the stability of electronic equipment. To determine safe areas for workers, laying communication cables and placing sensitive electronic equipment, it is advisable to model the propagation of magnetic fields of electrical machines. This will make it possible to rationalize the placing of electrical equipment at design stages. The most common high-power electrical machines are four-pole electrical machines with a dipole-quadrupole structure of the external magnetic field. **The purpose of the research** is a development of models of the propagation of the external magnetic field generated by alternating current electric machines. **Results of the research**: it is substantiated that to simulate the propagation of the magnetic field of electric machines, it is advisable to use the Gauss equation for the magnetic scalar potential. This will make it possible to take into account the required number of spatial harmonics of the magnetic field to ensure an acceptable calculation error. An electric machine is considered in a spherical approximation. Calculations were carried out in spherical coordinates. The distances were determined in relative radii of the electric machine - the ratio of the radius of the machine to the definition of field strength. The calculations were made for two planes of spherical coordinates and a three-dimensional image was obtained. As a result of the simulation, it is possible to determine the magnetic field strength of a four-pole electric machine at selected distances and directions around the electric machine with the required accuracy. It has been established that there are points of zero external magnetic field strength around electrical machines. Verification of the simulation results was carried out using the method of full-scale measurements of the magnetic field strength around a real four-pole machine. The measurement results showed acceptable agreement with the calculated data. **Conclusions:** the chosen approach and the results of modeling the propagation of the external magnetic field of electrical machines can be used to design the placement of electrical equipment, taking into account the requirements for electromagnetic safety and electromagnetic compatibility of technical equipment.

Keywords: electric machines; magnetic fields; modeling of propagation.

Introduction

Alternating current electric machines are very widespread electrical equipment. This is electricity generating equipment, electric drives for industrial and household use. Powerful electrical machines generate high-intensity external magnetic fields, which can have a negative impact on enterprise personnel and the public. In addition, magnetic fields from electrical equipment can disrupt the performance of electrical and electronic equipment, which does not meet modern electromagnetic compatibility requirements. All standard electrical machines have typical spatial structures of the external magnetic field, so any changes in its distribution indicate abnormal phenomena inside the machine (for example, interturn short circuits in the winding). Correct modeling of the propagation of an external magnetic field will allow solving of several applied problems: determining zones of safe stay and movement of people near electrical machines, determining the compliance of magnetic field strengths with the requirements of electromagnetic compatibility of equipment and providing a tool for diagnosing the technical condition of electrical machines. Modeling the propagation of magnetic fields will make it possible to determine the placement of equipment at a stages of design work in accordance with the requirements of electromagnetic safety and electromagnetic compatibility of electrical and electronic equipment. The main conditions for the correspondence of models to the real patterns of propagation of magnetic fields is the determination of the correct mathematical apparatus used to create software for modeling and modeling errors. For execution these conditions, it is advisable to investigate the possibility of using the Gauss equation for the scalar magnetic potential. This approach will allow us to take into account the influence of spatial harmonics of the magnetic field at its level, spatial distribution and the required number of harmonics depending on the size of the electric machine. Easy-to-use software will allow you to select the modeling error based on the principles of reasonable sufficiency. Modeling will allow you to choose a rational relative arrangement of equipment from the point of view of minimizing the influence of magnetic fields on people and the stability of electronic equipment in a complex electromagnetic environment.

Analysis of studies on modeling the propagation of magnetic fields of electrical equipment

The strengths of electric and magnetic fields of electrical and electronic equipment, as well as the total values of the fields of many sources, are regulated by the requirements of the European Electromagnetic Safety Directive [1], in particular, the mandatory annex to it developed by the International Commission on Non-Ionized Radiation. At the same time, certain requirements for radiation and resistance to electromagnetic interference are imposed on electrical and electronic equipment [2, 3]. At the same time, electrical and electronic equipment is subject to certain requirements for emissions and immunity to electromagnetic interference [2, 3]. Preliminary determination (prediction) of the electromagnetic situation when designing the placement of sources of electromagnetic fields in premises at the design stages is possible only by modeling the propagation of fields. At the same time, certain requirements for radiation and resistance to electromagnetic interference are imposed on electrical and electronic equipment [2, 3]. In the low-frequency part of the electromagnetic spectrum, the greatest practical importance is to determine a propagation of a magnetic component of an electromagnetic field of industrial frequency 50/60 Hz. An electrical component of such field is mainly shielded by the metal casings of the equipment, which have virtually no effect on the magnetic field strength. In addition, it is believed that the man-made magnetic field is more harmful to the human body.

Works on modeling magnetic field propagation conventionally can be divided into two categories: the field inside electrical equipment and the external magnetic field. Research into the distribution of the magnetic component of the electromagnetic field inside equipment is aimed at reducing energy losses and increasing the efficiency of equipment [4, 5]. In these studies, the commercial package COMSOL was used to model the magnetic field distribution. This is most preferable to ensure low modeling error in confined spaces of the transformer and high voltage cable. To model the propagation of the magnetic field of linear sources (overhead power lines), the method of reflection and determination of the magnetic field strength according to the Biot-Savart law is usually used [6, 7]. More accurate modeling of the magnetic field of a three-phase overhead line is achieved by considering the parallel wires of the line as a sequence of magnetic dipoles [8]. The MATLAB package was used in all these cases, but this approach is not acceptable for modeling the propagation of a magnetic field of complex configuration. Studies [9, 10] show the possibility of considering the field of any source as a combination of magnetic dipoles, which can be useful for determining the structure and propagation of magnetic fields of electric machines. The study [11] began to apply the Gauss equation for the scalar magnetic potential to determine the propagation of the magnetic field. It is also shown that the magnetic field of a four-pole electric machine has a dipole-quadrupole structure. This approach was implemented in [12, 13]. But modeling using the Gauss equation was carried out only in individual directions for certain fixed angles in polar coordinates, and the total magnetic field was presented in a qualitative (sketch) form.

To obtain easy-to-use two- and three-dimensional models of magnetic field propagation around electrical machines, it is necessary to determine a sufficient number of spatial harmonics of the magnetic field and the step of determining the intensity, for example, by angles in polar coordinates. It is necessary to ensure that a separate zone can be identified around the most critical electrical machine. Some articles discuss methods for adaptive resource allocation in cloud environments [14, 15], neural networks [16, 17] and the Internet of things [18, 19], which can be used in further research.

Purpose and objectives of the research. The purpose of the study is to simulate the propagation of an external magnetic field generated by AC electrical machines.

To achieve this aim, the following tasks were identified:

– selection of mathematical relationships and initial conditions underlying the modeling of the propagation of the external magnetic field of alternating current electric machines, the necessary critical parameters that ensure acceptable calculation errors, selection of software;

– creation of two- and three-dimensional models of external magnetic fields around the most common AC electrical machines, ensuring an acceptable modeling error depending on the relative size of the electric machine (the ratio of the size of the machine to the distance at which the magnetic field strength is determined).

Definition of mathematical functions for modeling the propagation of magnetic fields

The most common AC electrical machines are four-pole machines. Theyse include all turbogenerators, which are synchronous four-pole machines. So machines have the form of a magnetic field inherent in a quadrupole. Smaller machines may have eight poles and an octupole magnetic field shape. To model the propagation of magnetic fields and determine their strengths at any point, it is advisable to take into account the spatial harmonics of the magnetic field.

An electric machine can be considered in a spherical approximation (it is considered spherical, which is acceptable from the point of view of calculation error) [21].

Calculations are performed in spherical coordinates. The field strength at each point of the external magnetic field is the geometric sum of the radial and angular components of the magnetic field strength H_r, H_φ, H_θ. The value of amplitudes of spatial harmonics a_{nm} on the base sphere $R_0=1$ (machine radius) is used in practical calculations.

Magnetic field strength values are calculated sequentially for certain relative distances to the electrical machine R_0/R, where R is the actual distance.

Accurate determination of changes in magnetic field level with distance is useful using the Gauss equation for the scalar magnetic potential. In spherical coordinates R, θ, φ, the source magnetic field distribution function has the form:

$$U_M = R_0 \times \sum_{n=1}^{\infty} \left(\frac{R_0}{R} \right)^{n+1} \times$$

$$\times \sum_{m=0}^{n} \left(a_{nm} \cos m\varphi + b_{nm} \sin m\varphi \right) \times P_n^m \times \cos\varphi,$$

where R_0 is the radius of the sphere of determination of the potential, a_{nm}, b_{nm} are constant coefficients, and is the Legendre polynomial.

In this case, $R \geq R_0$ coordinates a, b are the amplitudes of the spherical harmonics of the magnetic field strength in the sphere R_0.

The magnetic field strength (induction) is determined from the above equation based on the fundamental relationships:

$$\boldsymbol{H} = -gradU_M,; \qquad \boldsymbol{B} = \mu_0 \boldsymbol{H};$$

$$H_r = \sum_{n=1}^{\infty}(n+1)\times\left(\frac{R_0}{R}\right)^{n+2}\times$$
$$\times\sum_{m=0}^{n}\left(a_{nm}\cos m\varphi + b_{nm}\sin m\varphi\right)\times P_n^m \times \cos\theta\ ;$$

$$H_\varphi = \sum_{n=1}^{\infty}(n+1)\times\left(\frac{R_0}{R}\right)^{n+2}\times$$
$$\times\sum_{m=0}^{n}\left(a_{nm}\cos m\varphi - b_{nm}\sin m\varphi\right)\times\frac{P_n^m\times\cos\theta}{\sin\varphi}\ ;$$

$$H_\theta = \sum_{n=1}^{\infty}(n+1)\times\left(\frac{R_0}{R}\right)^{n+2}\times$$
$$\times\sum_{m=0}^{n}\left(a_{nm}\cos m\varphi + b_{nm}\sin m\varphi\right)\times\frac{1}{\sin\varphi}\times$$
$$\times\left[(n-m+1)\times P_{n+1}^m\cos\varphi-(n+1)\times P_n^m\times\cos^2\theta\right];$$

These relationships indicate that the magnetic field strength decreases with distance, and this decrease is proportional to the increase in the harmonic index *n*.

Thus, based on the assigned tasks, it is advisable to consider the first spherical harmonics, which correspond to the slightest decrease in the magnetic field level with distance.

These are the dipole harmonic (n=1) and the quadrupole harmonic (n = 2).

The radial component of the magnetic field is determined from the given relations by a standard procedure using Legendre polynomials in the usual form.

For n = 1:

$$H_r^{(n=1)} = 2\times\left(\frac{R_0}{R}\right)^3\times$$
$$\times\left(a_{10}\cos\theta + a_{11}\cos\varphi\sin\theta + b_{11}\sin\varphi\sin\theta\right).$$

For n = 2:

$$H_r^{(n=2)} = \frac{3}{4\pi}\left(\frac{R_0}{R}\right)^4\times\left[\frac{a_{20}}{2}\left(3\cos^2\theta-1\right)+\right.$$
$$+3\left(a_{21}\cos\varphi + b_{21}\sin\varphi\right)\sin 2\theta +$$
$$\left.+12\left(a_{22}\cos 2\varphi + b_{22}\sin 2\varphi\right)\sin^2\theta\right].$$

These radial harmonics decrease with distance from the field source in proportion to the third and fourth powers of the radius.

A four-pole electric machine, in this case a turbogenerator, is a source of a magnetic field of the dipole-quadrupole type, that is, a source that has dipole and quadrupole spherical harmonics of the field. The magnetic field around such a source is characterized by the sum of harmonics $H_r^{(n=1)}$ and $H_r^{(n=2)}$.

The final value of the radial component (change in magnetic field strength with distance) of a four-pole electric machine is determined from the relationship:

$$H = \left(\frac{R_0}{R}\right)^3\times a_{11}\times\cos\varphi\times\sin\varphi + \left(\frac{R_0}{R}\right)^4\times$$
$$\times a_{22}\cos 2\varphi\times\sin^2\theta,$$

where a_{11} is the amplitude of the dipole harmonic of the magnetic field, a_{22} is the amplitude of the quadrupole harmonic.

For *a* real average power electric machine:

a_{11}≈400 А/м, a_{22}≈800 А/м.

Based on the values of these coefficients, the magnetic field propagation is modeled.

Modeling of spatial changes in the strength of the external magnetic field of a four-pole electric machine

A web application was developed in which the calculation part was performed using the Python language.

Calculations for visualization of simulation results are performed for angles φand θ polar coordinates ranging from 0 to 2π. The step for determining the magnetic field strength (number of points) is selected depending on the required accuracy (acceptable error).

The distances to the points for determining field strengths are selected based on the radius of the base sphere (the size of the electric machine in a spherical approximation). Calculations are made for the ratio R_0/R, that is, the distance is chosen in radii of the electric machine. Calculations were made for distances $R_0/R=1/2$ and $R_0/R=1/5$.

In Fig. 1 shows the magnetic field strength in the φ and θ planes and a three-dimensional representation of the spatial distribution of the field.

In Fig. 2 shows the magnetic field strength for the distance R_0/R = 1/5.

The presented representations are not always convenient for the practical application of models. Therefore, we visualized the change in the magnetic field in a fixed direction (for a certain angle) when changing another angle of polar coordinates for the distance $R_0/R=1/2$ (Fig. 3).

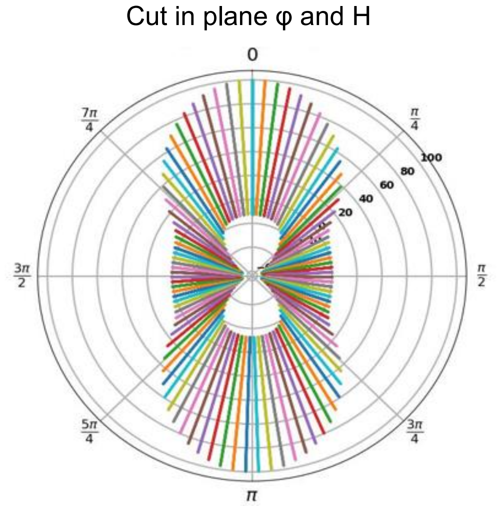
As can be seen from the obtained dependencies, the magnetic field strength changes differently in different directions.

This is explained by the complexity of the dipole-quadrupole field configuration. A significant practical result is the presence of certain angles of points of zero magnetic field strength [17]. So, for example, for φ=π and φ=2π the points of zero field strength correspond to θ values in π times.

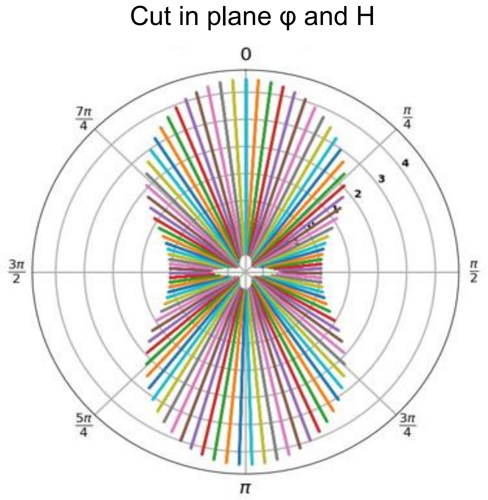
Verification of the simulation results was carried out using the method of full-scale measurements of a real four-pole electrical machine.

In Fig. 4 presents the results of measuring the magnetic field strength with distance from the electrical machine.

As can be seen from the results presented, the dependence of the magnetic field strength on the distance to the electric machine is non-monotonic. Near the machine there is at least one point of minimum tension.



a



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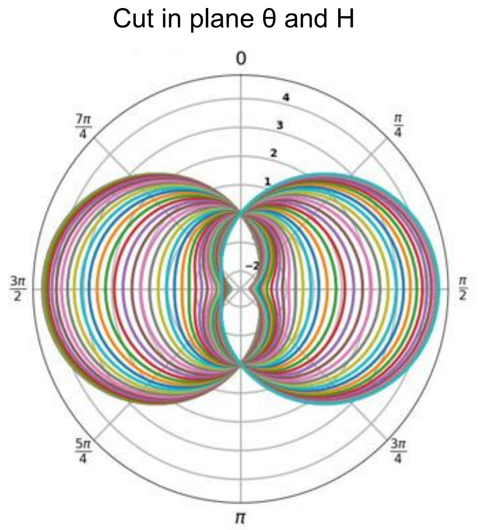

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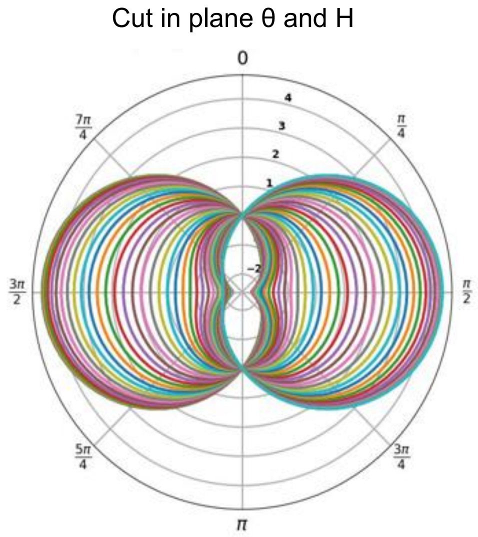

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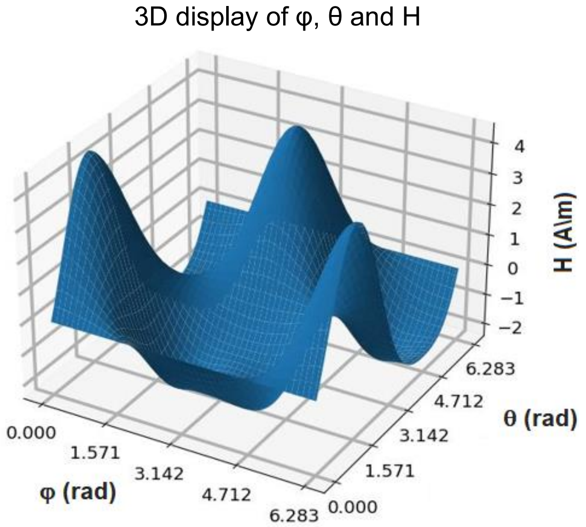
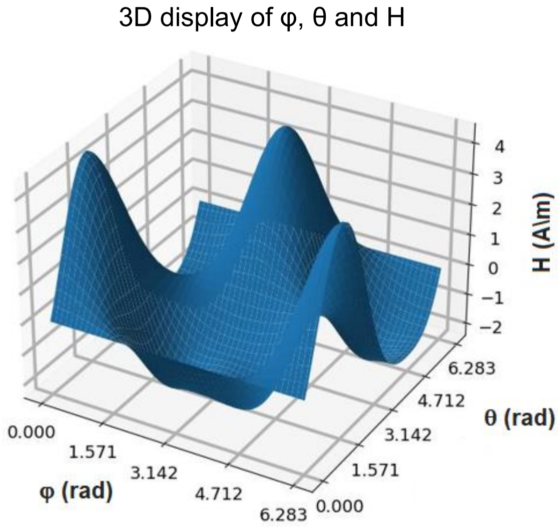


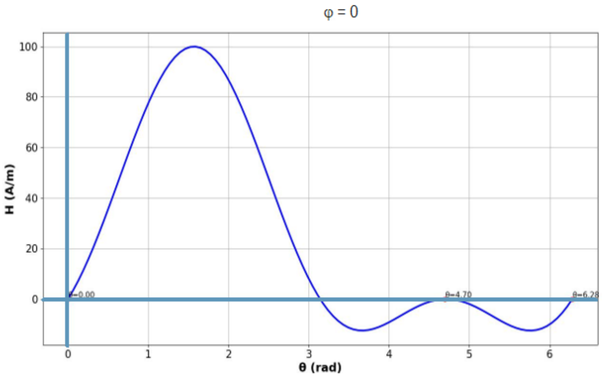
c



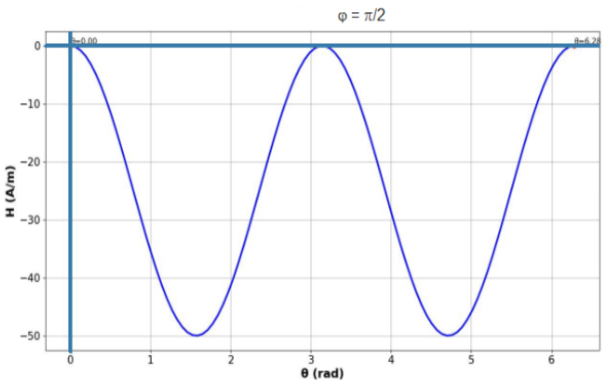
c

Fig. 1. Spatial distribution of the magnetic field strength of a four-pole electric machine at a relative distance $R_0/R=1/2$: A – magnetic field strength in the φ plane, b – magnetic field strength in the θ plane, c – three-dimensional representation of the field distribution

Fig. 2. Spatial distribution of the magnetic field strength of a four-pole electric machine at a relative distance $R_0/R=1/5$: a –magnetic field strength in the φ plane, b – magnetic field strength in the θ plane, c – three-dimensional representation of the field distribution



a



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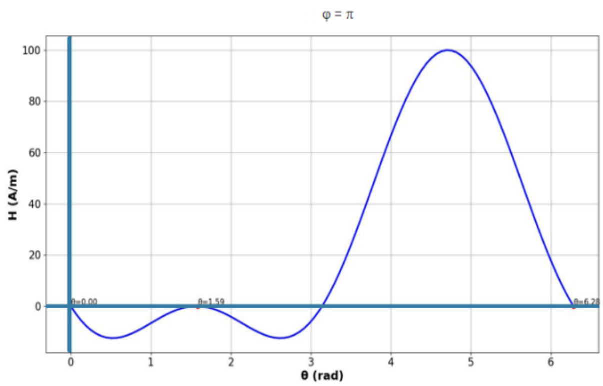

c

Fig. 3. Changes in the magnetic field strength of an electric machine in fixed directions: a, b, c correspond to angles φ=0; π/2; π

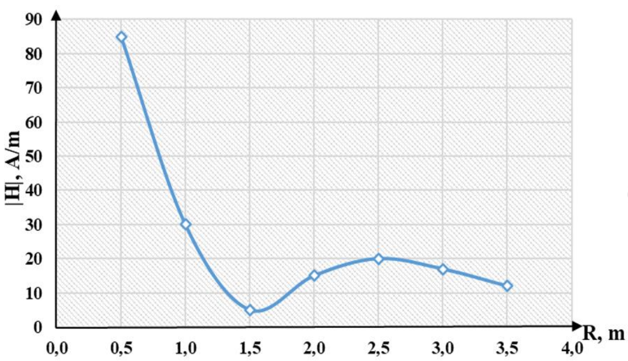

Fig. 4. Changing the magnitude of the magnetic field strength of the electric machine |H| with distance R from the body

Non-zero values of magnetic field strength can be explained by the presence of an electromagnetic environment - magnetic fields from other sources [18]. But the resulting curve indicates the adequacy of the modeling.

Discussion of the research results

As a result of the research, it was established that modeling the propagation of the external magnetic field of electric machines has acceptable convergence with experimental data. This allows you to design the placement of electrical equipment with minimal influence of magnetic fields on personnel.

Determining zones of minimum magnetic field strengths allows you to select locations for laying communication cables and placing electronic equipment in compliance with electromagnetic compatibility requirements. The availability of data on the distribution of magnetic field strengths in individual planes and directions simplifies the application of the results in engineering practice.

Based on deviations of the magnetic field structure from the standard configuration (for example, zero field points), one can conclude that abnormal phenomena have occurred inside the electrical machine. The obtained data can be used in the processes of reconstruction of energy facilities.

The orientation of the poles of an electric machine has a significant impact on the strength of magnetic fields in the planes of people's presence. Therefore, by orienting the entire electrical machine, it is possible to ensure minimum values of magnetic fields in the planes of residence and magnetically sensitive equipment.

The fulfilled work has certain limitations and disadvantages. A promising area of the researches is a creation of a database on the propagation of magnetic fields around electric machines of different sizes. It is possible by developing criteria to take into account a certain number of spatial harmonics of the magnetic field to ensure an acceptable calculation error. It is advisable to develop models of the propagation of magnetic fields around eight-pole electrical machines, which can be of great practical significance.

Conclusions

1. The Gauss equation for the magnetic scalar potential is advisable to use for simulating the propagation of an external magnetic field of alternating current electric machines. Taking into account the presence of spatial harmonics of the magnetic field allows to reduce the errors of the results obtained and determined the required number of spatial harmonics depending on the relative dimensions of the electric machine (the ratio of the size of the machine to the distance to the point at which the magnetic field strength is determined).

2. Obtaining two and three-dimensional models of magnetic field propagation provides possibility to select orientation planes of an electric machine with minimal influence of magnetic fields on personnel and sensitive electronic equipment. Based on the deviation of the magnetic field structure from that determined by

modeling, it is possible to diagnose the technical condition of the electric machine. Verification of modeling results using the method of full-scale measurements of magnetic field strengths has proven acceptable convergence of models with real propagations of magnetic fields around electrical machines.

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Моделювання зовнішнього магнітного поля електричних машин

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Анотація. Актуальність. Потужні електричні машини – такі як електрогенератори, електродвигуни створюють магнітне поле великої напруженості. Ці поля негативно впливають на персонал і можуть порушити стабільність роботи електронного обладнання. Для визначення безпечних зон для працівників, прокладки кабелів зв'язку та розміщення чутливого електронного обладнання доцільно змоделювати поширення магнітних полів електричних машин. Це дозволить раціоналізувати розміщення електрообладнання на етапах проектування. Найпоширенішими електричними машинами великої потужності є чотириполюсні електричні машини з диполь-квадрупольною структурою зовнішнього магнітного поля. **Метою дослідження** є розробка моделей поширення зовнішнього магнітного поля, створюваного електричними машинами змінного струму. **Результати дослідження**: обґрунтовано, що для моделювання розповсюдження магнітного поля електричних машин доцільно використовувати рівняння Гауса для магнітного скалярного потенціалу. Це дозволить врахувати необхідну кількість просторових гармонік магнітного поля для забезпечення прийнятної похибки розрахунку. Електричну машину розглядають у сферичному наближенні. Розрахунки проводились у сферичних координатах. Відстані визначалися у відносних радіусах електричної машини – відношенні радіуса машини до визначення напруженості поля. Розрахунки проводились для двох площин сферичних координат і отримано тривимірне зображення. В результаті моделювання можна з необхідною точністю визначити напруженість магнітного поля чотириполюсної електричної машини на обраних відстанях і напрямках навколо електричної машини. Встановлено, що навколо електричних машин існують точки нульової напруженості зовнішнього магнітного поля. Перевірку результатів моделювання проводили методом натурних вимірювань напруженості магнітного поля навколо реальної чотириполюсної машини. Результати вимірювань показали прийнятний збіг з розрахунковими даними. **Висновки**: обраний підхід та результати моделювання поширення зовнішнього магнітного поля електричних машин можуть бути використані для проектування розміщення електрообладнання з урахуванням вимог електромагнітної безпеки та електромагнітної сумісності технічного обладнання.

Ключові слова: електричні машини; магнітні поля; моделювання поширення.