Information systems modeling

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MODELLING THE PROPAGATION OF MAGNETIC FIELDS FROM MULTIPLE DIVERSE SOURCES

Abstract. Man-made magnetic fields have a negative impact on humans. When there are many sources of magnetic fields, their combined effects are unpredictable. The patterns of propagation of fields from different sources vary. This complicates the process of planning the placement of electrical equipment in specific areas. The most acceptable way to predict the electromagnetic environment at the design stages is to model the propagation of magnetic fields from multiple sources. **The aim of the study** is to model the propagation of magnetic fields from multiple sources with different patterns of spatial propagation. **Research results.** The most significant factor of constant influence on humans is extremely low frequency electromagnetic fields. At the same time, the magnetic component of these fields is not shielded by equipment housings. Therefore, it is advisable to model the propagation of the magnetic field. It is shown that all sources of the magnetic field can be considered as a combination of magnetic dipoles. To model the propagation of a dipole-type magnetic field, the ratio for the vector magnetic potential is used. To model the propagation of dipole-quadrupole-type magnetic fields, it is advisable to use Gauss's equation for the scalar potential. This allows the presence of spatial harmonics of the magnetic field to be taken into account. The propagation of the magnetic field in the plane where people are located was modelled. It has been established that even in the presence of field superposition, the change in magnetic field intensity with distance from each source is non-monotonic. There are zones of minimum and maximum field intensity. This allows the zones of safe human presence and the location of protective magnetic screens to be clearly defined at the design stage. Criteria for taking into account the required number of spatial harmonics of the magnetic field have been determined. This indicator is determined by the relative distance from the field source to its dimensions in a spherical approximation. **Conclusions.** The mathematical functions determined and used in the process of modelling the propagation of magnetic fields from multiple sources provide an acceptable modelling error. In the process of modelling the propagation of quadrupole-type magnetic fields in a given plane, the spatial orientation of the field sources should be taken into account. The field structure for electric machines in a plane is determined by the orientation of the machine poles relative to the selected plane.

Keywords: modelling; magnetic field; dipole; quadrupole.

Introduction

Modelling the propagation of electric, magnetic and electromagnetic fields is an effective method for predicting the electromagnetic environment and the stages of designing the placement of electrical and electronic equipment in territories and premises. This makes it possible to minimise the impact of such fields on the population and personnel and to incorporate protective measures into design solutions. Such measures include rationalising the placement of equipment, determining safe areas for people to stay and move around, and installing electromagnetic screens. The basis for modelling is the correct determination of mathematical functions for the spatial propagation of electromagnetic fields from sources of different designs and operating principles, field superposition, etc. This is due to the different patterns of spatial propagation of fields from different sources and their different intensities at the source. It is impossible to combine and visualise the propagation of extremely low frequency electromagnetic fields (industrial and its harmonics) and ultra-high frequency electromagnetic fields (wireless communication) due to different units of measurement: low-frequency fields are characterised by field intensities (induction), while high-frequency fields are characterised by energy flux density. The most pressing task is to determine the spatial distribution of extremely low frequency electromagnetic fields due to their constant impact on people. This includes the functioning of technological equipment and life support systems in buildings, as well as household appliances. All these sources are located inside buildings and structures, and their electromagnetic fields directly affect people. Therefore, it is advisable to automate the process of assessing the electromagnetic environment in conditions where the population and personnel of enterprises are exposed to electromagnetic fields from many sources with different amplitude values.

Analysis of research and publications

Most studies on modelling the propagation of electromagnetic fields are aimed at solving problems of electrical equipment stability and energy conservation. Work [1] considers the fields of cable power lines from the point of view of electrical insulation stability. Study [2] concerns the propagation of a magnetic field, taking into account its partial shielding by a coating. Work [3] is devoted to the propagation of magnetic fields of overhead power lines, providing calculations for their shielding by regular metal structures. The studies cited concern distributed sources of electromagnetic fields. The mathematical apparatus for calculating their quantitative values and propagation patterns differs from the indicators of sources localised in space. Such sources include all radio equipment and devices for generating, converting and driving electricity. In [4], the principles of modelling the propagation of electromagnetic fields of radio-technical objects of civil aviation are presented. The radiation directionality diagrams of such objects do not intersect. Therefore, it makes no sense to consider the integral values of their impact on people. The patterns of propagation of such fields are similar to the propagation of electromagnetic fields from mobile communication base stations. However, in areas where the directional patterns of individual stations intersect, the total energy flows are small [5]. This is because the location of base stations is optimised in terms of signal strength to ensure communication. The sources of such fields, both in industrial and domestic conditions, are localised in space and close to people. These are transformers, electric drives, heating devices, etc. In most cases, the electric component of such fields is shielded by metal equipment housings, and the electric component propagates in the environment. Therefore, the propagation of industrial frequency magnetic fields and their harmonics is mainly studied. Works [6, 7] present the results of modelling the magnetic fields of transformer cores and magnetostriction phenomena due to changes in the magnetic field. These models were created using finite element methods with COMSOL and ANSYS software packages. This is due to the need for high modelling accuracy in a limited volume. High accuracy in modelling the propagation of external magnetic fields is not necessary to ensure human safety. Studies [8, 9] have shown that the magnetic field of any source can be represented by a combination of magnetic dipoles. This fact is used to model the external magnetic field of a four-pole electric machine, which is dipole-quadrupole [10]. In particular, the acceptable convergence of the modelling results with the experiment is shown. In [11], the modelling of the propagation of magnetic fields from heterogeneous sources has been partially implemented, but it only concerns the external fields of power lines and transformers and high-frequency emitters in territories. They cannot be considered as a complete picture of the electromagnetic environment in certain areas. The electric component of the ultra-low frequency electromagnetic field is usually shielded by metal equipment housings. The magnetic component freely propagates beyond the boundaries of electrical devices and machines. Therefore, it is advisable to simulate the propagation of the magnetic field of many heterogeneous sources located in a limited area.

The aim of the work is to simulate the propagation of magnetic fields from multiple sources with different spatial propagation patterns.

Presentation of the main material

To simulate the propagation of an electromagnetic field, it is necessary to correctly determine the mathematical functions that describe the propagation of fields from different sources. As mentioned above, most sources of low-frequency magnetic fields have a shape characteristic of magnetic dipoles. It is advisable to perform calculations in a single plane corresponding to the plane in which people are located.

We consider the sources of the magnetic field to be localised in space. The magnetic field induction vector $\vec{B}$ is determined by the relationship:

$$rot\vec{A} =$$
$$= \left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z} \right)\vec{i} + \left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x} \right)\vec{j} + \left(\frac{\partial A_z}{\partial x} - \frac{\partial A_x}{\partial_y} \right)\vec{k},$$

where $\vec{i}, \vec{j}, \vec{k}$ – unit vectors.

The components of the magnetic field induction are determined from the relationship:

$$B_x = (\nabla \times A)_x =$$
$$= \frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z} = -\frac{\partial}{\partial z} \cdot \frac{mx}{(x^2 + y^2 + z^2)^{3/2}} = \frac{3mxz}{r^5},$$

$$B_y = (\nabla \times A)_y =$$
$$= \frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x} = \frac{\partial}{\partial z} \cdot \frac{-my}{(x^2 + y^2 + z^2)^{3/2}} = \frac{3mxz}{r^5},$$

$$B_z = (\nabla \times A)_z = \frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} = m \times$$
$$\times \left[\frac{-2x^2 + y^2 + z^2}{(x^2+y^2+z^2)^{5/2}} + \frac{x^2 - 2y^2 + z^2}{(x^2+y^2+z^2)^{5/2}} \right] = \frac{m \cdot (3z^2 - r^2)}{r^5}.$$

where m – dipole magnetic moment of the field source, r – distance to the point of determination of the magnetic field induction.

Considering the xz plane for $y = 0$ we determine that, $\sin\theta = x/r$, $\cos\theta = z/r$, where θ – is the angle between the coordinate axis and the direction to the point of determination of the magnetic field induction. In this case:

$$B_x = \frac{3m \cdot sin\theta \cdot cos\theta}{r^3}, \quad B_y = 0, \quad B_z = \frac{m \cdot (3cos^2\theta - 1)}{r^3}.$$

To obtain several data on magnetic field induction, the values of the dipole magnetic moment of each field source are required.

Its standard definition is given by the ratio:

$$\vec{m} = \frac{\mu_0}{4\pi} I\vec{S},$$

where I – electric current in the circuit; $\vec{S}$ – directed area of the section covered by the circuit.

This definition is ineffective due to the complexity of electrical equipment, computer hardware, backup power sources, peripheral devices, etc.

Therefore, for each magnetic field source, it is advisable to determine the magnetic moment experimentally by measuring the magnetic field strength (induction) at a fixed distance:

$$H = m \Big/ \left(2\pi\mu_0 r^3 \right),$$

where H is the experimentally determined magnetic field strength at a distance r from the source, μ_0 is the magnetic constant.

$$m = 2\pi\mu_0 H r^3 = 2\pi B r^3 \;\; \left(B = \mu_0 H \right)$$

A significant number of ultra-low frequency magnetic field sources generate fields that differ in shape from dipole fields. For example, the fields of electric machines with different numbers of poles (more than two) have a dipole-quadrupole or dipole-octupole structure. For such sources, the correct determination of the magnetic field propagation requires taking into account the spatial harmonics of the field. This is possible by applying Gauss's equation for scalar potential. The source of the magnetic field is considered in a spherical approximation, i.e., it is considered to be a sphere of radius R_0. The magnetic field of such a source is calculated as the geometric sum of the radial and angular components of the magnetic field H_r, H_θ, H_φ in polar coordinates.

$$U_M = R_0 \times \sum_{n=1}^{\infty} \left(R_0/R\right)^{n+1} \times$$
$$\times \sum_{m=0}^{n} \left(a_{nm} \cos m\varphi + b_{nm} \sin m\varphi\right) \times P_n^m \times \cos\varphi,$$

where R_0 – nominal radius of the magnetic field source, R – distance to the field determination point, a, b – coefficients characterising the amplitude values of the field of the corresponding harmonics, P_n^m – Legendre's polynomial. The components of magnetic field intensity (induction) are calculated based on fundamental relationships:

$$H = -gradU_M, \quad B = \mu\mu_0 H,$$

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

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

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

To ensure an acceptable calculation error, it is important to determine a sufficient number of spatial harmonics of the field that must be taken into account. The intensity of the field decreases with distance in proportion to the index n. It has been established that for a relative distance index $R_0/R = 0{,}1$, even the second harmonic does not exceed 0.05 of the first. That is, in real conditions, when the distances from individual sources are large, it is sufficient to take into account the values of the dipole harmonic *(n = 1)* and the quadrupole harmonic *(n = 2)*. In this case:

$n = 1$:

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

$n = 2$:

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

Spherical harmonics are represented in a similar way. To obtain a two-dimensional model in the plane where people are located, the value of one spherical harmonic is taken into account.

Modelling of the propagation of ultra-low frequency magnetic fields was performed in Visual Studio 2019. Programming language C#. SQL Server DBMS was used. The user interface is implemented as a web application using HTML5 markup language, CSS cascading style sheets, and Java Script programming language.

The database contains data on the dimensions of the plane on which the magnetic field sources are located, the coordinates of these sources and their dimensions. In addition, data on the magnetic field strength at a fixed distance from the sources, which are determined experimentally or from other sources, are entered. This is necessary to calculate the magnetic moment of the dipole source of the magnetic field. If the source of the magnetic field is more complex and the field has a dipole-quadrupole shape, then the amplitude values of the corresponding spatial harmonics are entered into the tables. An example of modelling the propagation of a magnetic field from multiple sources is shown in Fig. 1.

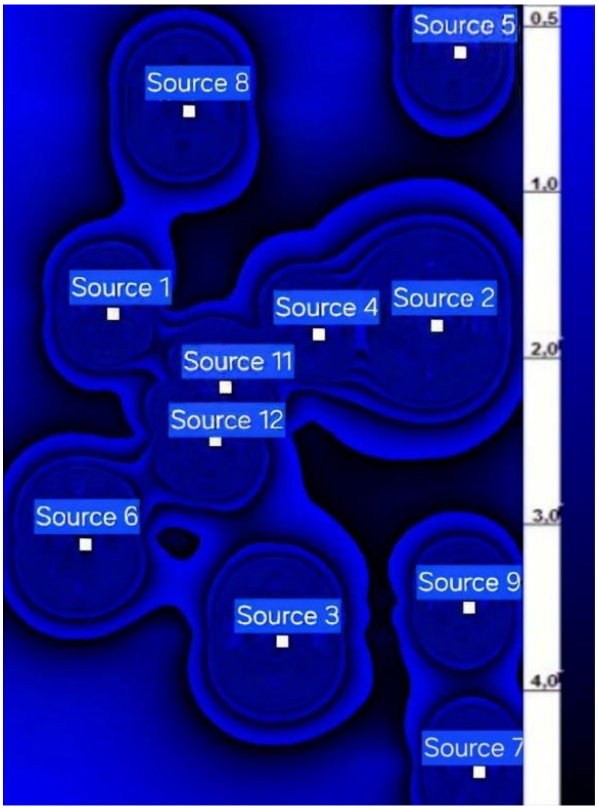

Fig. 1. Propagation of an extremely low frequency magnetic field around many electrical devices; magnetic field induction values are represented on a colour scale in μT

The simulation results show that magnetic field intensities change non-monotonically with distance from the sources. A decrease in field strength is followed by an increase.

This is consistent with the fundamental principles of electrical engineering. For example, the amplitude of the dipole harmonic near an electric machine is 0.2 times that of the fundamental. However, its decrease with distance is slower, so there are points or surfaces where the values of the harmonics equalise and the dipole harmonic continues to prevail. In this zone, the direction of the field intensity vector changes to the opposite, passing through zero, which is reflected in the model. This result has practical significance. In the process of designing the placement of equipment on production floors or territories, it is possible to determine zones of safe stay and movement of people. In the case of high magnetic field intensities, magnetic screens are located at certain distances from the field sources in the zones of maximum intensity.

In areas with dense magnetic field sources – 1, 4, 11, 12 (Fig. 1) and small relative distances from them, it may be necessary to take into account the stresses of fields of harmonics higher than the second in order to reduce modelling errors.

Table 1 shows the relative level of higher spatial harmonics depending on relative distances.

Table 1 – **Relative level of higher spatial harmonics of the magnetic field at different relative distances from the source**

R_0/R	K						
	n=2	n=3	n=4	n=5	n=6	n=7	n=8
2/3	3,33	2,22	1,48	0,99	0,66	0,44	0,29
1/2	2,50	1,25	0,63	0,31	0,16	0,08	0,04
1/3	1,67	0,56	0,19	0,06	0,02	-	-
1/4	1,25	0,31	0,08	0,02	-	-	-
1/5	1,00	0,20	0,04	-	-	-	-

In practical applications, the number of spatial harmonics of the field should be taken into account to ensure an acceptable modelling error. The total magnetic fields of many sources, such as electric motors and generators, are asymmetrical with respect to the orientation of the poles in space.

For different planes in spherical coordinates θ and φ, the spatial distributions of the magnetic field in the plane will be different.

The propagation of magnetic fields of dipole-quadrupole structure is shown in Fig. 2.

In Fig. 2, sources 1 and 3 are of the same type. However, in the plane of field propagation, the spatial distributions of the fields of these sources differ. This is due to the different orientations of the planes of the poles of the electric machine.

When such devices are located close to each other, the structure of the total field is complex (Fig. 3).

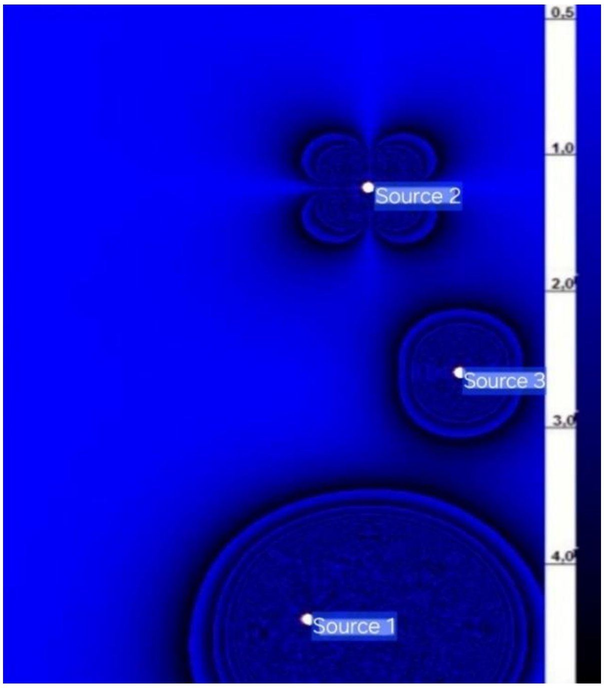

Fig. 2. Propagation of the magnetic field around sources of dipole-quadrupole structure

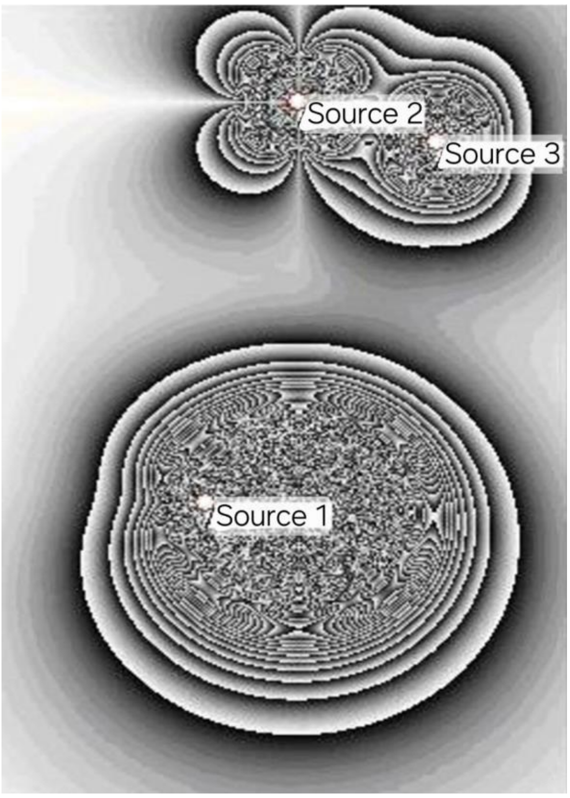

Fig. 3. Spatial distribution of the magnetic field of two electric machines with different pole orientations

As can be seen in Fig. 3, the total field has a complex structure. It is practically impossible to determine it by experimental methods.

This is especially true for the design of electrical equipment placement in limited areas. Field propagation modelling makes it possible to identify areas of equal field intensity and allows for the unambiguous determination of the location of protective structures.

To correctly simulate the propagation of magnetic fields from multiple sources, it is necessary to have accurate data on the magnetic dipole moment of each source. This is achieved by measuring the field strength of similar sources that are in operation.

There is some ambiguity in choosing the number of spatial harmonics of the magnetic field to be taken into account. Increasing the number of harmonics taken into account reduces the modelling error but significantly increases the number of calculations. This complicates the optimisation of equipment layout schemes in specific areas.

The most rational approach is to select the number of spatial harmonics of the magnetic field based on the actual field strengths of individual pieces of equipment. The criterion is the maximum permissible magnetic field strengths for a given type of source. If the isolines of the field excess values of neighbouring sources intersect, there is no point in considering additional harmonics. If no field intensity excess is observed, it is advisable to determine the contribution of higher spatial harmonics to the total magnetic field of several pieces of equipment.

In practical activities involving the modelling of the propagation of magnetic fields of technological equipment, the presence of electromagnetic background from external sources in rooms and territories should be taken into account.

Conclusions

1. Mathematical functions that are most suitable for modelling the propagation of ultra-low frequency magnetic fields have been determined. For dipole-type field sources, the dipole moment of each source is required. It is determined from experimental data on the magnetic field strength of a typical source at a fixed distance. For dipole-quadrupole, octupole, and other types of magnetic field sources, it is advisable to use Gauss's equation for scalar potential. This allows the contribution of spatial harmonic fields to the total magnetic field to be taken into account. To perform the modelling, the value of the magnetic field intensity at the base distance is required. The magnetic field source is considered in a spherical approximation. The ratio of the amplitude values of the higher harmonics relative to the fundamental is determined.

2. Modelling the propagation of ultra-low frequency magnetic fields around multiple sources shows that even the total magnetic fields change non-monotonically with distance from the field sources. Determining the isolines of minimum magnetic field values allows us to identify safe areas for people to stay and move around. It is advisable to use areas of maximum magnetic field intensity for the placement of protective magnetic screens.

3. It has been shown that the spatial distribution of magnetic fields of dipole-quadrupole type sources differs in different planes of spherical coordinates. When determining the spatial distributions of magnetic fields in the planes where people are located, it is necessary to take into account the orientation of the electric machine relative to the plane, which is determined by the location of the machine's poles. The number of spatial harmonics taken into account in modelling is selected based on the principle of reasonable sufficiency. Increasing the number of harmonics taken into account reduces the modelling error, but also leads to an increase in the volume of calculations, which complicates the process of optimising the placement of electrical equipment.

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Моделювання поширення магнітних полів множинних різнорідних джерел

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Анотація. Магнітні поля техногенного походження є чинником негативного впливу на людей. При наявності багатьох джерел магнітного поля їх сумарні значення непередбачувані. Закономірності поширення полів різнорідних джерел відрізняються. Це ускладнює процес планування розміщення електричного обладнання на визначених площах. Найбільш прийнятним способом прогнозування електромагнітної обстановки на стадіях проєктування є моделювання поширення магнітних полів багатьох джерел. **Метою дослідження** є моделювання поширення магнітних полів багатьох джерел з різними закономірностями їх просторових поширень. **Результати дослідження.** Найбільш вагомим чинником постійного впливу на людей є електромагнітні поля наднизької частоти. При цьому магнітна складова цих полів не екранується корпусами обладнання. Тому доцільно здійснити моделювання поширення магнітного поля. Показано, що усі джерела магнітного поля можна розглядати як комбінацію магнітних диполів. Для моделювання поширення магнітного поля дипольного типу використано співвідношення для векторного магнітного потенціалу. Моделювання поширення магнітних полів дипольно-квадрупольного типу доцільно застосувати рівняння Гауса для скалярного потенціалу. Це дозволяє враховувати наявність просторових гармонік магнітного поля. Здійснено моделювання поширення магнітного поля у площині перебування людей. Встановлено, що навіть за наявності суперпозиції полів зміна напруженості магнітного поля з відстанню від кожного джерела немонотонна. Існують зони мінімальної та максимальної напруженості поля. Це дозволяє на стадіях проєктування однозначно визначити зони безпечного перебування людей та місця розташування захисних магнітних екранів. Визначено критерії врахування необхідної кількості просторових гармонік магнітного поля. Цей показник визначається відносною відстанню від джерела поля – до його розмірів у сферичному наближенні. **Висновки**. Визначені математичні функції, покладені у процес моделювання поширення магнітних полів багатьох джерел забезпечують прийнятну похибку моделювання. У процесі моделювання поширення магнітних полів квадрупольного типу у визначеній площині слід враховувати просторову орієнтацію джерел поля. Структура поля для електричних машин у площині визначається орієнтацією полюсів машини відносно обраної площини.

Ключові слова: моделювання; магнітне поле; диполь; квадруполь.