UDC 621.319

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Calculation apparatus for modeling radio engineering and electrical engineering objects

The proposed approach makes it possible to unambiguously determine the location of zero field points at a certain distance from the source (for a quadrupole source and zero field lines, for an octupole source). The results of modeling and its verification by field measurements for the most common four-pole machines (quadrupole source) are presented.

Introduction. Radio engineering and electrical objects are widely used on the territory of airports. These are electric generators, electric motors of various purposes and power. Determining the spatial distributions of their magnetic fields makes it possible to assess the possible impact on people, energy losses, etc. At the stages of designing the placement of equipment in the airport premises such an assessment is possible by modeling the distribution of fields. A feature of modeling the propagation of ultra-low magnetic fields (power frequencies, its harmonics and interharmonics) is the need to ensure the required accuracy of the final result. In industrial premises with limited space, it is necessary to accurately determine the zones of safe stay of people. The required accuracy of modeling can be ensured by taking into account a sufficient number of spatial harmonics of the magnetic field.

Analysis of recent research and publications. The modeling the propagation of magnetic fields in radio technical and electrical equipment aimed at reducing energy losses, concerns the distribution of the magnetic field inside the device and is performed using the Comsol package [1, 2]. Studies on taking into account the spatial harmonics of the magnetic field of electrical machines [3] have shown that this approach is promising. In most cases, models of the most common dipole-type field sources are considered [4, 5]. But most electrical and radio technical objects are sources of quadrupole and even octupole magnetic fields, but the field configurations in it are sketchy [6]. But any source of a magnetic field can be considered as a combination of magnetic dipoles with different magnetic moments [7]. The works [8, 9] used the synthesis of the magnetic field of technical objects based on spatial harmonics. In this case, it is necessary to take into account the relative sizes of the sources in order to determine the required number of spatial harmonics.

Presentation of the main material. In real conditions, in addition to the industrial frequency, there are harmonics and its harmonics (third and multiples of three). In electrical machines of any design, harmonics can always be distinguished in accordance with the number of poles of the machine: dipole, quadrupole, octupole (n=1, 2, 3). An accurate determination of changes in the level of the magnetic field with distance is expedient using the Gauss equation for a scalar magnetic potential. In spherical coordinates R, θ, φ, the source magnetic field distribution function has the form:

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

де R_0 – the radius of the sphere of the determination the potential, a_{nm}, b_{nm} – constant coefficients $P_n^m \cos\varphi$ –Legendre polynomial.

In doing so, R ≥ R_0, the coordinates a, b are the amplitudes of the spherical harmonics of the magnetic field strength in the sphere R_0. The strength (induction) of the magnetic field is determined from the above equation based on the fundamental relationships: $\boldsymbol{H}=-gradU_M$, $\boldsymbol{B}=\mu_0\boldsymbol{H}$

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

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

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

The above relations 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 tasks set, it is advisable to consider the first spherical harmonics, which correspond to the slightest decrease in the level of the magnetic field 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 above relations by a standard procedure using the Legendre polynomials in the usual form.

For n=1:

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

For n=2:

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

The magnetic field around a four-pole electric machine is characterized by the sum of harmonics $H_r^{(n=1)}$ and $H_r^{(n=2)}$. In general:

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

Thus, the dependence of the field strength on the distance for different angles of spherical coordinates will differ significantly: for $\theta = \frac{\pi}{2}\left(\sin\theta = 1,\ \sin^2\theta = 1\right)$ in the direction φ=0 dipole and quadrupole harmonics are added, and in the direction φ=π – are subtracted. The result obtained is important from the point of view of ensuring the electromagnetic safety of personnel located near power generators. That is for at φ=π there is a point where H=0, that is, within this angle, the total levels of the fields are insignificant. Considering the change in the field strength by φ=0 and φ=π, assuming R_0=1, we obtain the relation:

$$H_1 = \frac{a_{22}}{R^4} + \frac{a_{11}}{R^3}, \quad H_2 = \frac{a_{22}}{R^4} - \frac{a_{11}}{R^3}.$$

The result obtained indicates that, under the condition φ=π, as a result of different rates of decrease in the strength of the dipole and quadrupole components of the magnetic field with distance, there is a point where H = 0. Modeling of the spatial distribution the magnetic field a four-pole electric machine using the Matlab package for φ=π, R=2. For a dipole-octupole field, its zero value can be on closed lines. In the plane θ=π/2, there is only one component of the magnetic field H_0 with exponents n = 1,3:

$$H_0 = H_{010} + H_{030} = \left(\frac{R_0}{R}\right)^3 \times \left[\frac{3}{2}\left(\frac{R_0}{R}\right)^2 a_{30} - a_{10}\right],$$

That is, in the plane θ in the angle 0<φ<2π along the entire circle H_0=0 on a distance: $\frac{R}{R_0} = \sqrt{\frac{3a_{30}}{2a_{10}}}$. Accounting for a large number of spatial field harmonics allows you to calculate the field strength at any point around the electric machine and indicate them graphically. Minimizing the number of harmonics taken into account reduces the volume of calculations and simplifies the field propagation modeling processes. In the presence of a dipole harmonic, the maximum value of the field strength H_φ is achieved at φ=0, θ=π/2:

$$H_\varphi = \frac{1}{4\pi} \times \left[b_{nn}\left(\frac{R_0}{R}\right)^{n+2} + b_{11}\left(\frac{R_0}{R}\right)^3\right].$$

As shown in [7], the relative level of higher spatial harmonics:

$K = \frac{H_{nn}}{H_{11}} = \frac{b_{nn}}{b_{11}} \times \left(\frac{R_0}{R}\right)^{n-1}$, and given that: $b_{11} = 0{,}2b_{nn}$, $K = 5\left(\frac{R_0}{R}\right)^{n-1}$.

That is, it is possible to calculate the relative level of higher spatial harmonics for any ratios R_0/R (Table 1).

Table 1

The relative level of the higher spatial harmonics of the magnetic field K for different relative distances from the electric machine

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	-	-	-	-

As can be seen from the table, for smaller relative dimensions of the electric machine a smaller number of spatial harmonics should be taken into account. For example, for R_0/R=2/3 even the eighth harmonic gives about 30% of the first, and for the second R_0/R=1/5 the fifth harmonic becomes insignificant.

This makes it possible to rationalize the processes of modeling the spatial propagation of magnetic fields of electrical machines with the necessary accuracy (permissible error) for determining the field strengths at any point.

Conclusions. It is shown that in order to ensure the required accuracy when modeling the field propagation (permissible error), one should take into account the relative dimensions the electric machine (the ratio of the conditional radius of the machine to the distance of determining the magnetic field strength). At smaller relative sizes, a smaller number of spatial harmonics is taken into account. This simplifies the process of modeling the propagation the field depending on its objectives.

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