COMPARATIVE ANALYSIS OF METHODS OF CALCULATING MAGNETIC SYSTEMS USING ELECTROMAGNETIC FIELD THEORY

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Abstract
In the article, almost all methods used for calculating magnetic circuits with movable parts are considered and their advantages and disadvantages are defined. It is also based on the possibility of obtaining quick and high-accuracy results by using special computer programs in the calculation of magnetic circuits.

Keywords: magnetic circuit, electromagnetic field theory, analytical calculation methods, magnetic field modeling, finite element method.

Due to the structure of magnetic circuits and their diversity, as well as the fact that the devices in which magnetic systems are used perform different tasks, it is not possible to develop a separate method for calculating these magnetic circuits. Until now, there are several methods of calculating magnetic circuits, among them, the methods of calculating magnetic circuits using electromagnetic field theory allow us to obtain results closer to practice than other methods, so we will consider the process of comparative analysis of these methods. We will also develop an instruction on the appropriateness of using these methods.

According to the appearance and presence, the electromagnetic field is divided into several types, and their structure scheme is presented in Figure 1.

The field that produces stationary electric charges is considered an electrostatic field, leading scientists L.A. Bessonov, O.B. Bull, T.A. Thatur, K.S. Demirchyan, L.R. Neumann, N.W. Korovkin, V.L. Chechurin, G.I. Atabekov, S.D. Kupalyan, A.V. Timofeev and S.S. Kikhrikov studied and N.N. Mirolyubov, M.V. Kostenko, M.L. Levinstein and N.N. Tikhodeev has analyzed in detail the methods of calculating the processes related to this field.

Fields without mechanical motion and transient modes are stationary fields. A stationary magnetic field can be studied separately as a stationary electric and magnetic field. They do not affect each other. Stationary magnetic field name was suggested by L.A. Bessonov, T.A. Thatur, K.S. Demirchyan, L.R. Neumann, N.W. Korovkin, V.L.Chechurins. A constant current magnetic field was put forward by G.I. Atabekov, S.D. Kupalyan, A.V. Timofeev and S.S. Kikhrikov in the studies carried out, it was called a time-invariant magnetic field in the literature written by English scientists, it was called magnetostatic. In addition, the stationary area was opened by J.L. Coulomb and J.K. Sabonnadiere's researches, descriptive calculations were carried out with the help of scalar magnetic potential or vector potential.

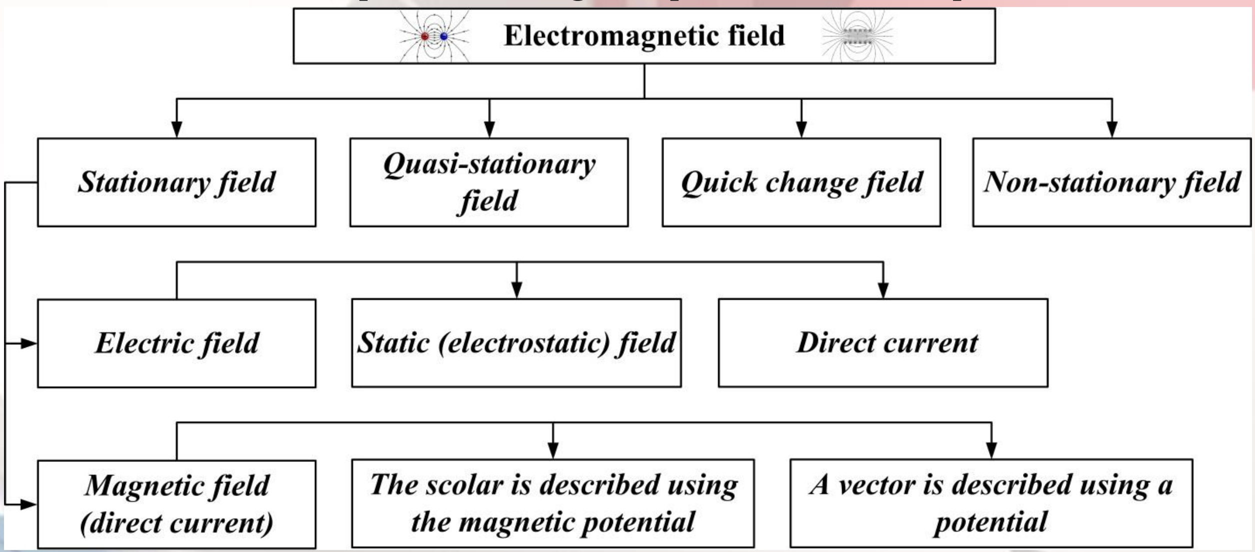

Fig. 1. Types of electromagnetic field

A field whose parameters change sinusoidally over time is considered a quasi-stationary electromagnetic field, and in this case, the effects of radiation and current displacement may not be taken into account. This field theory was developed by K.S. Demirchyan, L.R. Neumann, N.W. Korovkin. It was studied in the details by Chechurins. In the literature written by English scientists, the quasi-stationary electromagnetic field is called time-harmonic or harmonic. A quasi-stationary electromagnetic field occurs in most of the electrical equipment operating at industrial frequency.

The field where radiation effects and current drift must be taken into account is a rapidly changing field. Any electromagnetic field listed above can be considered as a non-stationary electromagnetic field in the transient mode (when the voltage is applied to the set point). The structural scheme of the calculation of electromagnetic fields is presented in Fig. 2, and some of these methods are conditionally included in the chain theory method. For more information on chain theory methods, see leading scientists B.K. Bull, I.S. Taev, A.G. Gyodjello, G.W. Butkevich, A.G. Slivinskaya, G.N. Alexandrov, V.V. Borisovich, V.L. Ivanov, E. Kallenbach's research results.

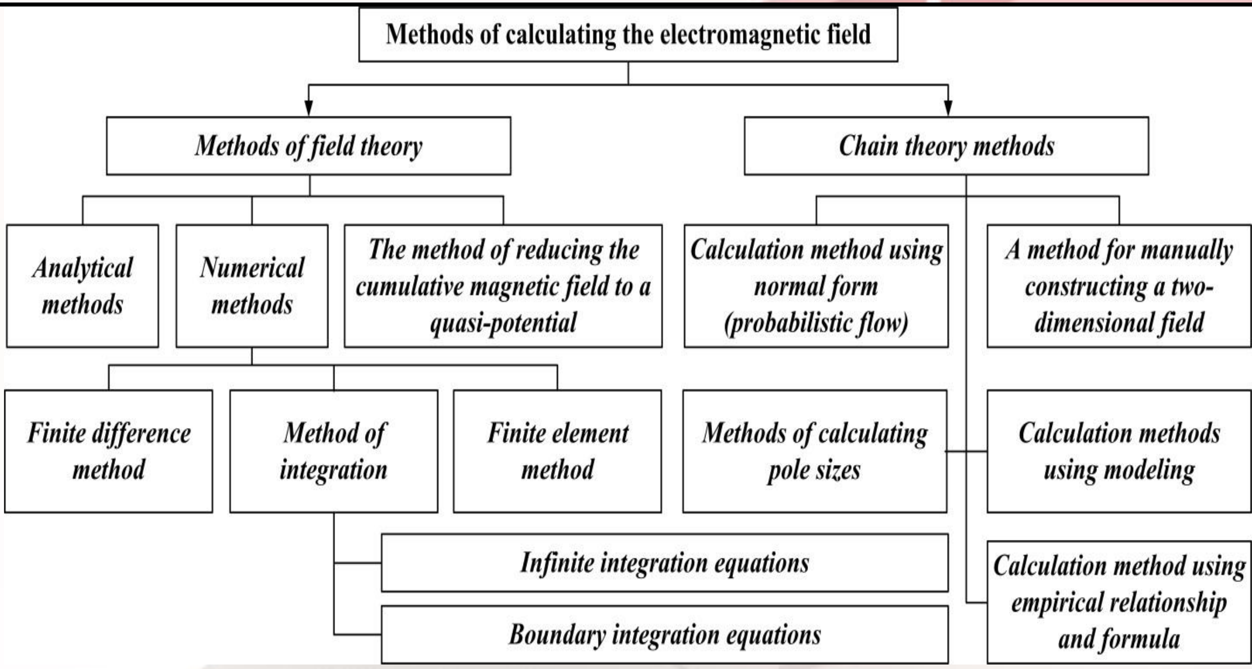

Fig. 2. Methods of calculating the electromagnetic field

Figure 3 shows the classification of the methods of constructing a two-dimensional view of the magnetic field, and Figure 4 shows the schematic diagram of the modeling of the magnetic field using an electric model.

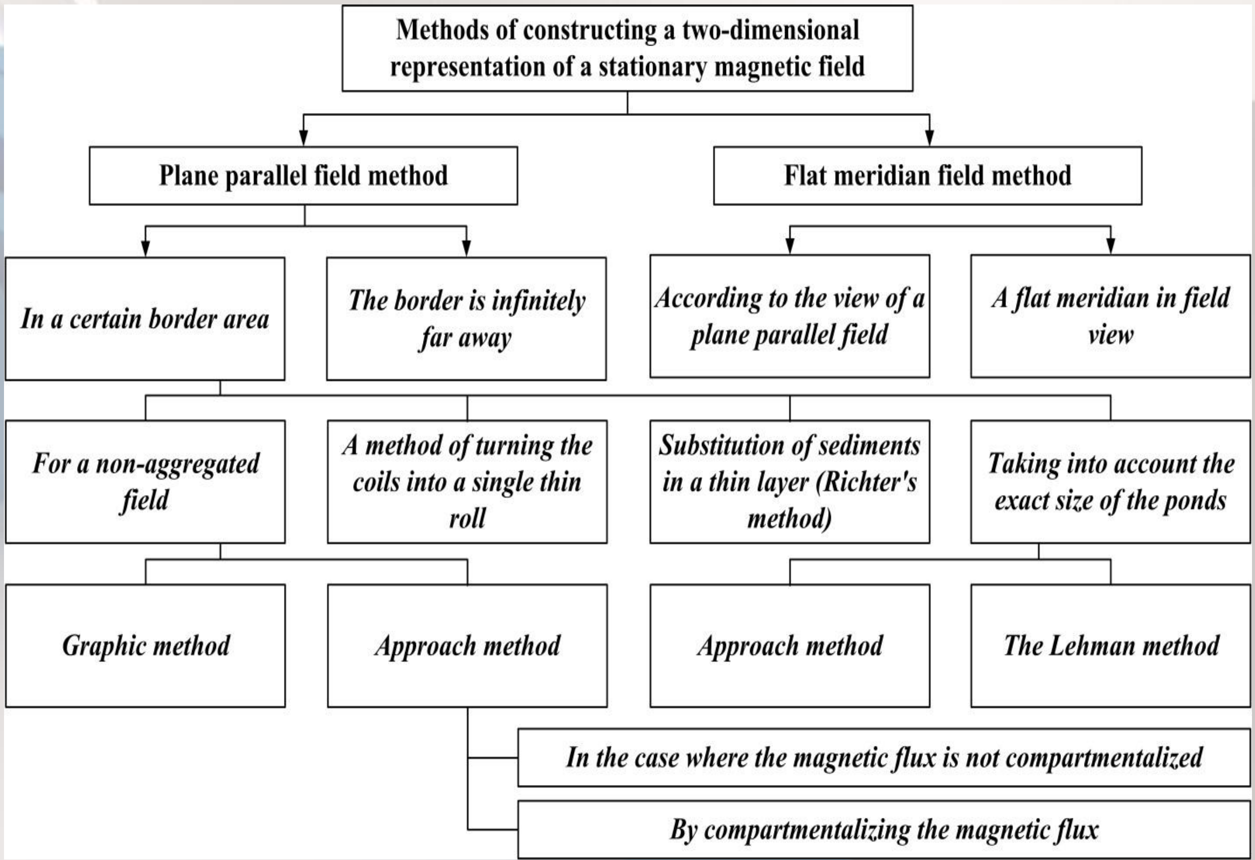

Fig. 3. Methods of constructing a two-dimensional view of the magnetic field

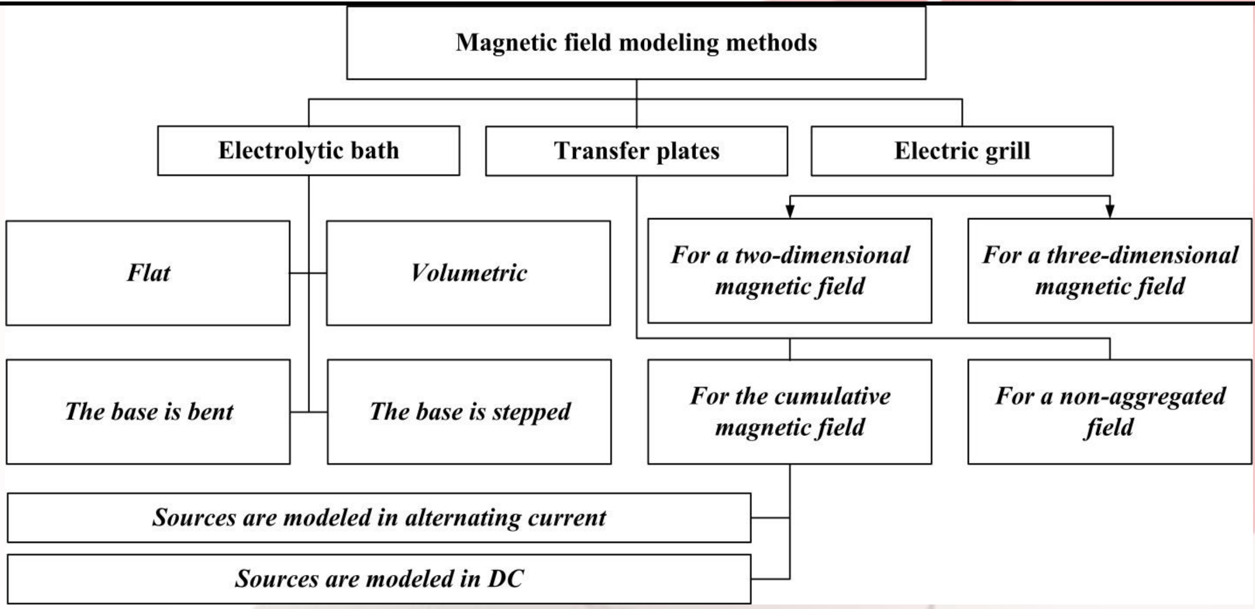

Fig. 4. Methods of modeling the magnetic field using an electric model.

The main classification of the methods of analytical calculation of the electromagnetic field is presented in Fig. 5. Information about the advantages and disadvantages of these methods and their use can be found in L.A. Bessonov, V.A. Govorkov, T.A. Tatur, K.S. Demirchyan, L.R. Neiman, N.V. Korovkin, V.L. Chechurin, G.I. Atabekov, S.D. Kupalyan, A.V. Timofeev, S.S. Khikhrikov, B.L. Alievsky, V.L. Orlov, N.N. Mirolyubov, M.V. Kostenko, M.L. Levinstein and N.N. Tikhodeev. The literature on the electromagnetic field written by Ratters is covered in detail.

Analytical methods in the calculation of magnetic circuits allow obtaining a numerical result for any value of the variable in the resulting expression, but these results are appropriate only for a few simple cases or the resulting expression is so complex that it can only be processed using special computer programs and the results as a curve must be described.

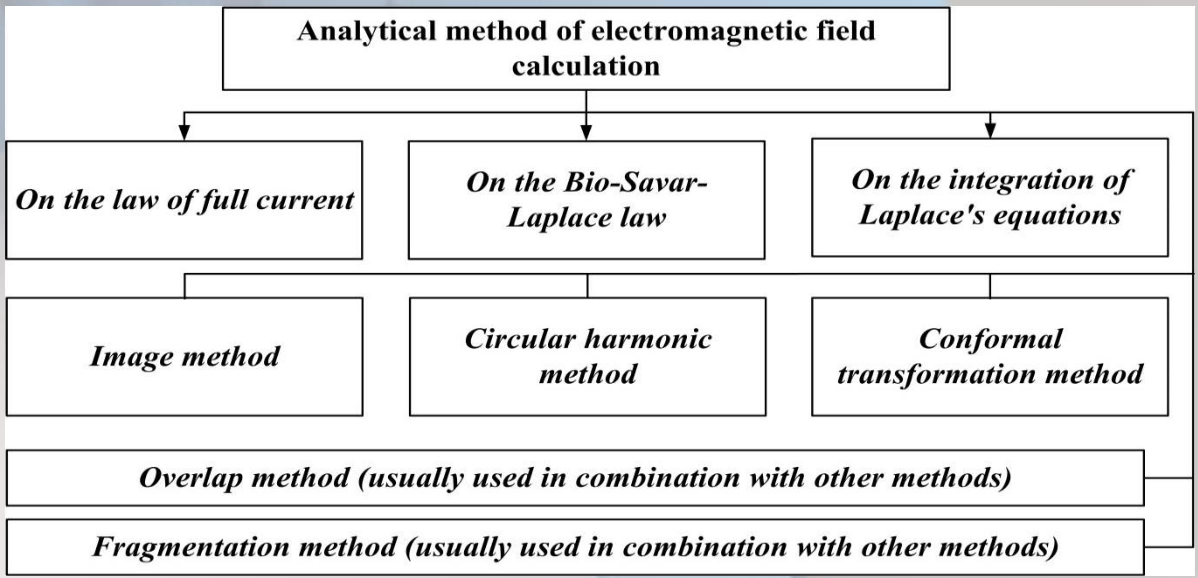

Figure 5. Analytical methods of electromagnetic field calculation

Analytical methods of calculating the electromagnetic field are almost not used nowadays, instead numerical methods are widely used.

The literature written by L.A. Bessonov, T.A. Tatur, G.I. Atabekov, S.D. Kupalyan, A.V. Timofeev, S.S. Khikhrikov contains information about the finite difference method, which is one of the numerical methods for calculating the electromagnetic field. In this literature, the finite difference method is called the grid method. The main essence of this method is that the magnetic field to be calculated is divided into certain rectangular squares (looks like a grid) and the magnetic potentials at each point are determined using the following equation of Laplace.

$$\frac{\partial^2 \varphi_м}{\partial x^2} + \frac{\partial^2 \varphi_м}{\partial y^2} = 0$$

The strength of the magnetic field at any point and edge of the magnetic field through magnetic potentials can be determined using the following expression.

$$H = -grad\varphi_м.$$

To achieve a high-precision result, the step of the grids should be very small. That is why the number of cells in the grid is significantly larger when solving a specific problem. Also, the number of equations and unknowns to be solved is equal to the number of nodes in the grid. Determining the field strength for the case of 106 nodes is challenging even for today's modern computers.

Using the finite difference method, it is also possible to calculate fields in a medium with a nonlinear description, and in this case, the derivatives of the potentials at the boundary boundaries are assumed to be zero.

Errors in the calculation of the magnetic field by the finite difference (grid) method occur due to the following reasons:

- uncertainty of correlation equations of potential points;
- the value of the magnetic field strength is determined by differentiating the field potentials, which in turn leads to the erroneous determination of the value of the calculated quantity;
- mainly applies to electromagnetic devices, and an additional error occurs in the calculation of magnetic fields whose boundary is at an infinite distance.

The finite difference (grid) method was used earlier than other numerical methods. They even used the finite difference method to manually calculate the flat area. This method is developed quite perfectly, and about it V.A. Govorkov, K.S. Demirchyan. More detailed information is given in the literature written by the Chechurins. In recent years, the development of methods that provide better results compared to this method and the calculation process is partly simpler (integration, finite elements) has led to a decrease in interest in using the grid method in magnetic field calculation. Using integration methods, it is possible to calculate the magnetic field in an inhomogeneous medium (air, coil, magnetic conductor, etc.) by bringing it to a homogeneous medium (air or vacuum). In this case, the inhomogeneity is changed to the secondary sources of the magnetic field, i.e. to induced eddy currents, magnetic charges, surface or bulk current density source. There are two different approaches to calculating the electromagnetic field using this method (boundary and infinite integration equations). In the first method, the electromagnetic field is calculated according to a certain boundary condition, and in the second method, the calculation is carried out based on an iterative scheme, taking into account the nonlinearity of sections of magnetic systems. More detailed information on this method is given in the literature written by P.A. Kurbatov.

The next method that provides high results in the calculation of the electromagnetic field is the finite element method. In this method, the surface occupied by the magnetic field in two-dimensional problems is divided into separate pieces with very small edge sizes with straight and curved lines, and in three-dimensional problems with planes and curved protrusions. When solving two-dimensional problems, the finite elements are triangles or rectangles, and when solving three-dimensional problems, they consist of parallelepipeds and tetrahedrons with all side surfaces of triangles.

The following methods are used to formulate equations for calculating the magnetic field using the finite element method:

- method of minimizing several functionals;
- method of weighted residuals (Galerkin method);
- the method of least squares.

The Galerkin method is based on differential equations for the scalar magnetic potential, and the functional minimization method is based on the minimization of the energy in the magnetic field. After determining the magnetic potential at any point of the magnetic field using appropriate methods, the magnetic field strength and other parameters of the field are determined.

Through the methods discussed above, it is possible to obtain results with a certain level of accuracy in calculating the electric field. But it takes a lot of time to calculate. Therefore, a computer program based on the finite element method was developed, which allows obtaining the highest level of results in the calculation of the electromagnetic field among these methods. There are also computer programs based on the calculation of the electromagnetic field based on the method of integration, and P.A. Kurbatov. Information about these methods in literature written by Kulaev is provided.

Currently, ANSYS, FEMM, Ansoft, Vector Fields, Cosmosm, FEMLAB, ELCUT, Somsol multiphysics and other computer programs based on the calculation of the electromagnetic field using the finite element method have been developed. These programs are divided into two groups, i.e. special programs for calculating the magnetic field and general purpose programs. The programs based on the first group have been studied by several famous scientists, and the fact that these programs are designed to calculate only two-dimensional areas causes the limitation of the scope of the problem.

Programs belonging to the second group have significantly wider possibilities compared to the programs of the first group, and they are difficult to understand and use. But with the help of these programs, it is possible to get a high-level result that is very close to practice. Among them, ANSYS, Ansoft, Vector Fields, Cosmosm programs are very expensive in terms of price, and ANSYS program is widely used in the world. In the literature prepared by D. Mekeer, there is information on the calculation of the area using the FEMM program. This program is superior in terms of ease of use compared to other programs.

With the help of the programs mentioned above, it is possible to solve the following issues:

- calculation of linear and non-linear magnetic field;
- calculation of alternating current magnetic field taking into account cumulative currents;
- electric field calculation;
- calculation of current distribution in a conductive medium;
- calculation of linear and non-linear thermal conductivity;
- linear analysis of the state of compression and elongation.

Magnetic circuits and devices with electromagnetic screens can be used to calculate the magnetic field in magnetic systems using all the methods that allow to get high results. But in cases where it is necessary to further increase the level of accuracy, it is appropriate to use computer programs based on the calculation of the electromagnetic field using the finite element method.

By conducting a comparative analysis of the calculation methods of magnetic systems with electromagnetic shields using electromagnetic field theory, it was found that it is possible to achieve results close to practice through integration methods and finite element methods. It is also desirable to calculate magnetic circuits and devices with an electromagnetic screen using the methods mentioned above (computer program or manually).

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