Investigation of Electric Reactor Magnetic Field using Finite Element Method

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Introduction

Continuously raising requirements to development and manufacture of electrical engineering devices demand more detailed studying of electromagnetic processes occurring in them.

Recently one of the most powerful means of modelling of field processes in various devices and complexes are packages of the finite element analysis FEA.

The best approach of the numerical decision parameters of the real device can be obtained by means of three-dimensional modelling in which all three spatial coordinates are considered.

Finite elements method provides sufficient accuracy of electromagnetic field computation and very well flexibility when geometry is modelled and field sources are loaded.

Mathematical model of industrial object magnetic field computation

Wave length of an electromagnetic field of industrial frequency $\lambda = c/f = 6 \cdot 10^6$ m (where $c = 3 \cdot 10^8$ km/s - a velocity of light in a vacuum; $f = 50$ Hz - the industrial frequency) much more exceeds the characteristic sizes of power device installations.

Therefore, electrical and magnet fields of industrial frequency can be investigating as quasi-static. The electrical and magnet fields can be analyzed separately by analysis of potentials and currents of wires. The magnetic field distributed in the researched system agreeably to the Ampere's law

$$\text{rot } \boldsymbol{H} = \boldsymbol{J}, \qquad (1)$$

where $\boldsymbol{H}$ - magnetic field strength; $\boldsymbol{J}$ - density of current which creates magnetic field.

The system, in which the total magnetic field of power installations is created, represents various cuts of wires (bus arrangements), with complicate space orientation, and also any number of overground installations. The ground on which one the power installation is fitted has influence to magnetic field distribution, too.

The boundary conditions must be specified accurately on the surfaces of equipment which is analyzed. When problem of magnetic field distribution is performed by the equation (1) the boundary conditions must be determined agreeably with magnet field permeation character inward medium. At interacting of the magnetic field with steel constructions, which have the electric conductivity $\sigma = 10^7$ S/м and a relative permeability $\mu_r = 5000$, the skin depth is $\approx 0,32$ mm. In the depth equal to 5 mm the field is decreased approximately in $6 \cdot 10^6$ times, i.e. the magnetic field in the steel practically is absent. Therefore, we can suppose that following boundary condition is true on the steel surface:

$$H_n = 0, \qquad (2)$$

i.e., the normal to body surface component of magnetic field vector H_n is equal to zero.

In the parts with copper (or aluminium) current carrying conductors, which have the electric conductivity $\sigma = 5,8 \cdot 10^7$ S/м and relative permeability $\mu_r = 1$, a skin depth is about 10 mm that matches with the field reduction in 1,7 times on depth of 5 mm (the field are essentially decreased in dimension comparable with current carrying parts dimensions of electrical industrial network equipment). At the same time magnetic field distortion by the metallic constructions happens in rather local size. From the point of view of ecological impact of industrial frequency magnetic fields such magnetic field distortions can be unvalued.

Therefore, when magnetic field around the power equipment is computing the sizes of current carrying leads can be neglected. We can suppose that current is concentrates on lead axis. These currents are evaluated in a right side of the equation (1). The currents induced in current carrying parts by external magnetic fields can be neglected, too.

The skin depth has ten centimeters or of unity of meters in the non-metallic parts (concrete structures) and in the

ground because of the low ground electric conductivity and absence of magnetic properties ($\mu_r = 1$). Therefore the magnetic field permeates into a ground almost without loosening and the availability of a ground can be not evaluated, computing the magnetic fields of power equipment.

Peculiarities of dangerous for human power equipment magnetic field computation

When the ecological situation must be evaluated the magnetic field computation has some peculiarities. We must evaluate total magnetic field in all space around power equipment to assess the most dangerous for human points. There are:
- Three-dimensional character of the field;
- Complexity of magnetomotive force sources system which one can include many tens or hundreds solids and units;
- The diverse shape and dimensions of solids and units which compose magnetomotive force sources system. This system can include the leads one geometrical size of which 10 times and more exceeds remaining (phase conductors, bus arrangements, units of substations etc.);
- Existing sanitary regulations restrict levels of a field strength from a land surface at the altitude 1,8 m. Therefore the significant interest presents magnetic field allocating in immediate proximity from electrical engineering systems near to which one people can be.

The analysis of three-dimensional electromagnetic problems by finite element method

The software package ANSYS can be used for investigation of the magnetic field distribution (the magnetic flux density, the magnetic field strength and the magnetic vector potential) and the basic electromagnetic characteristics (inductance and electromagnetic force) of electric devices.

The decision of problems in the given package is made on the basis of the finite elements method (FEM). Three-dimensional models are created on the basis of vector or scalar magnetic potentials (it depends on type of elements meshing).

In ANSYS package algorithms for two formulations of electromagnetic problems are realized: vector (Magnetic Vector Potential - MVP) and scalar (Magnetic Scalar Potential - MSP).

Magnetic vector potential method (method MVP) in comparison with a method of scalar potential (method MSP) is more difficult in realization of model, and also gives smaller accuracy in the models containing areas with various magnetic permeability [3].

Method MVP it is realized by means of finite elements of type SOLID97 in software package ANSYS. The areas occupied by current leads are a part of finite element model, and their parameters are set as a constants (Real Constants) of corresponding finite elements. Method MSP is realized using finite elements of type SOLID96 and SOLID98. In this case the areas occupied by current leads are not included in finite element model. They are set by special finite elements type SOURC36 which geometrical

space can be crossed with space of a finite element mesh of model [2, 3].

For the problems decision on the scalar magnetic potential basis in package ANSYS three strategy are used:
1) Reduced Scalar Potential (RSP) Strategy;
2) Difference Scalar Potential (DSP) Strategy;
3) General Scalar Potential (GSP) Strategy.

The distinction among these strategy consists in some simplifications of the field modelling equations. Strategy of the decision must be set by the user at a stage of the decision. Correctness of results of computation depends on this choice [4].

Computation of electric reactor magnetic field

The frequency of reactor is low, therefore, this problem is magnetostatic. In a three-dimensional case it is described by elliptic equation Laplace - Poisson. The essence of this equation solution by the method of finite elements consists in a finding correct approximation of vector potential components $A_x (x, y, z)$, $A_y (x, y, z)$ and $A_z (x, y, z)$ by basic functions inside of the finite element In the cartesian coordinate system the equation which must be approximated is [4]:

$$\nabla^2 \boldsymbol{A}(x, y, z) = u(x, y, z), \qquad (3)$$

where $\boldsymbol{A}(x,y,z)$ – vector-potential of a magnetic field, $(x,y,z) \in V$ (V – modelling volume), $u(x, y,z)$ – the right part depending on currents which create the magnetic field.

For the magnetostatic problems the boundary conditions can be of the first sort $\boldsymbol{A}(x, y, z) = f_1 (x, y, z)$, or the second sort: $\partial \boldsymbol{A} (x,y,z) /\partial \boldsymbol{n} = f_2 (x, y, z)$, where $\boldsymbol{n}$ is a normal to the boundary surface. Expression (3) in the cartesian coordinates system for electromagnetic processes can be written as [4]:

$$\frac{1}{\mu_r} \left(\frac{\partial^2 \boldsymbol{A}}{\partial x^2} + \frac{\partial^2 \boldsymbol{A}}{\partial y^2} + \frac{\partial^2 \boldsymbol{A}}{\partial z^2} \right) = -\mu_0 \boldsymbol{J}, \qquad (4)$$

where μ_r – relative magnetic permeability of a model material, μ_0 – magnetic constant, $\boldsymbol{J}$ – current density.

On the basis of a finite element method package the three-phase electric reactor with the air core was investigated (see Fig. 1).

Fig. 1. Air electric reactor (phase "C")

Electrical reactors are electrical devices the primary purpose of which is to introduce inductive reactance into a high voltage circuit. They are used in electrical power transformation and distribution systems as well as in the control and communication systems. The air core reactor is used to limit the short circuit current. It can be the consumer of reactive power when it is necessary to

increase transmission line capability. The air core reactors are serial-connected to power line [1].

Magnetic field of reactor can sometimes reach the values dangerous to human. The coils of reactor are manufacturing separate for every phase. The three phase coils are distributed one over other. The coils are separated by support insulators this way, that mutual inductivity among windings could be significantly less then coil inductivity. Depending on nominal current the coils can have one or some parallel turns [1].

Electromagnetic computation of the electric three-phase reactor was performed by means of program complex ANSYS. It was necessary to calculate inductance of three windings of a reactor. Model of the electric reactor is shown in Fig. 2.
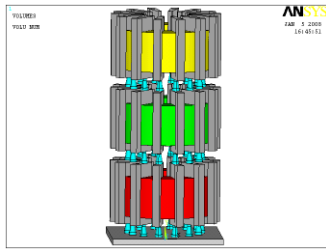

Fig. 2. View of electric reactor

Type of the analysis was chosen magnetostatic, with the open space, three-dimensional. Calculation was performed by a method of scalar magnetic potentials with use of 8-central final elements SOLID96 specially intended for this method. They fill all space inside of model (air, volume of a winding, the base, concrete columns of windings) [2].

SOLID96 has the capability of modeling 3-D magnetic fields. The geometry, node locations, and the coordinate system for this element are shown in Fig. 3. The element is defined by eight nodes and the material properties. A tetrahedral-shaped element may be formed by defining the same node numbers for nodes M, N, O, and P; and nodes K and L. A wedge-shaped element and a pyramid-shaped element may also be formed as shown in Fig. 3.
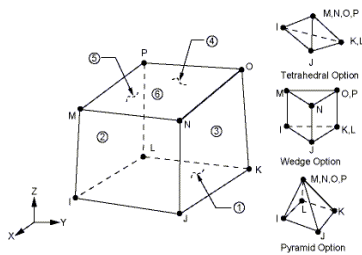
.

Fig. 3. Geometry of SOLID 96 elements

The certainly-element grid is created in a mode of free construction. Therefore final elements are applied in the particular kind - in the form of tetrahedrons (tetrahedrons) with four units instead of eight. By symmetry of the electric reactor half of its model is considered [2].

Parameter of meshing quality is $SmS = 10$. Number of finite elements of the model is obtained $n_{f.e.} = 853618$ and the number of nodes - m $n_{n.} = 178349$. The place occupied by windings was modeled by finite elements

SOLID96 which are used for non-magnetic space modelling.

Each of reactor phase windings is presented by means of macros "Racetrack", representing the three-dimensional current finite elements by serial connection of two half of hollow cylinders. Use of macros "Racetrack" enables to build model of solid-state volumes and to present values of a current of windings in the form of a variable more close by the end of a brief, that in the further simplifies the interactive analysis of system at different values of a current.

The infinite space on model is limited by the surfaces of the continuous round cylinder distanced from windings of a reactor on distance 1.5 m along axes x and y; and 0.5m along the axis z.

The finite element mesh of the electric three-phase reactor is shown in Fig. 4. Because investigated system is without magnetic core the method of Reduced Scalar Potential (RSP) were used.
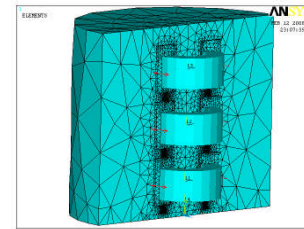

Fig. 4. Finite-element model of an investigated electric reactor

Relative magnetic permeability of air and the volumes occupied by windings, columns of windings and the basement was accepted to equal unit. The number of coils of any winding was equal to $N=144$ and a current was equal to $I=131A$ in windings of a reactor. The environment of modelling of the electric reactor was chosen linear isotropic. The magnetic flux is parallel to vertical planes of symmetry (zy and zx) and perpendicular a horizontal plane of symmetry xy. The last is provided because the scalar magnetic potential of the plane xy is accepted equal to zero.

The magnetic field distribution inside and outside of the reactor was obtained. In Fig.5 and in Fig.6 there are presented the distribution of the values (Fig. 5) and the direction (Fig. 6) of magnetic flux density inside and outside of reactor. Arrows around of windings specify the direction of the current in windings. The greatest values of the magnetic flux density ($B = 0,0465$ T)were obtained on the vertical axis of the electric reactor.
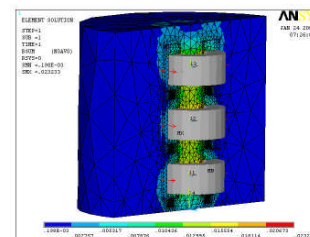

Fig. 5. Distribution of magnetic flux density values (windings are not shown)

Removing from the reactor vertical axis the value of the magnetic flux density decreases proportional to a

second power of distance from the magnetic field source (see Fig.7 and Fig. 8). On surface of model the magnetic flux density is equal to $B = 396$ μT. Because the half of model of a reactor was modelled, the obtained results must be doubled.
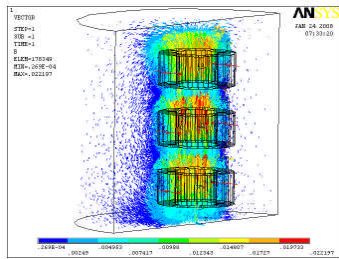

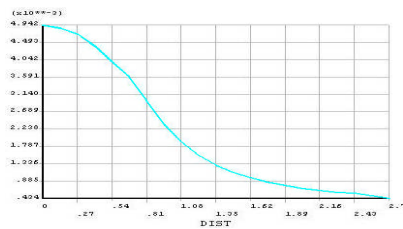**Fig. 6.** Distribution of magnetic flux density vector

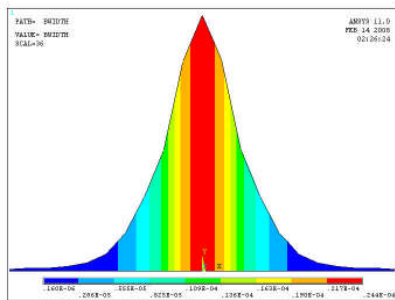**Fig. 7.** Dependence of magnetic flux density on, x when $y = z = 0$

Fig. 8. Magnetic flux distribution on axis x

Conclusions

1. Finite elements method (FEM) provides sufficient accuracy in computation of the magnetic field characteristics and very well flexibility when the geometry is modelled and the sources of magnetic field are loaded.
2. It is more preferable to use a method of scalar magnetic potential because it is more convenient in realization of model and gives greater accuracy then vector magnetic potential.
3. Using the regular triangular mesh the computation of the magnetic field distribution on area of the electric reactor becomes considerably simpler.

References

1. **Morozionkov J., Virbalis J. A.** Magnetic Field of Power Plant Air Core Reactor // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 7(79). – P. 67–70.
2. **Saeed Moaveni.** Finite Element Analysis. Theory and Application with ANSYS. – Mankato: Minnesota State University, 1999. – P. 527.
3. **Андреева Е. Г., Шамец С. П., Колмогоров Д. В.** Конечно-элементный анализ стационарных магнитных полей с помощью программного пакета ANSYS. – Омск: Изд-во ОмГТУ, 2002. – 92 с.
4. **Буль О. Б.** Методы расчета магнитных систем электрических аппаратов. Программа ANSYS. – Москва: Академия, 2006. – С. 286.

J. Morozionkov, J. A. Virbalis. Investigation of Electric Reactor Magnetic Field using Finite Element Method // Electronics and Electrical Engineering. – Kaunas: Technologija, 2008. – No. 5(85). – P. 9–12.

Raising requirements to development and manufacture of electrical engineering devices the introduction of complex program packages for calculation and optimization of their design must be doing in process of development. One of the most powerful means of electromagnetic field processes modelling in various devices are packages of the Finite Element Analysis. The three-dimensional model of the electric reactor in the cartesian system of coordinates for scalar magnetic potential was investigated using package ANSYS. Ill. 8, bibl. 4 (in English; summaries in English, Russian and Lithuanian).

Е. Морозенков, Ю. А. Вирбалис. Исследование магнитного поля электрического реактора методом конечных элементов // Электроника и электротехника. – Каунас: Технология, 2008. – № 5(85). – С. 9–12.

Повышающиеся требования к разработке и производству электротехнических устройств требуют внедрения в процесс разработки сложных программных комплексов для расчёта и оптимизации их конструкции. Одним из мощнейших средств моделирования полевых процессов в различных устройствах являются пакеты конечно-элементного анализа (Finite Element Analysis – FEA). Исследована трёхмерная модель электрического реактора в декартовой системе координат для скалярного магнитного потенциала пользуясь программным пакетом ANSYS. Ил. 8, библ. 4 (на английском языке; рефераты на английском, русском и литовском яз.).

J. Morozionkov, J. A. Virbalis. Elektrinio reaktoriaus magnetinio lauko tyrimas baigtinių elementų metodu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008. – Nr. 5(85). – P. 9–12.

Gaminant elektrotechninius įrenginius reikalingi sudėtingi programų paketai jų konstrukcijoms skaičiuoti ir optimizuoti. Viena iš galingiausių priemonių modeliuojant elektromagnetinius procesus įrenginiuose yra baigtinių elementų analizės programų paketai. Atliktas elektrinio reaktoriaus trimačio modelio tyrimas Dekarto koordinačių sistemoje skaliarinio magnetinio potencialo metodu, naudojant programų paketą ANSYS. Il. 7, bibl. 4 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).