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Method for design of two-level system of active shielding of power frequency magnetic field based on a quasi-static model

Aim*. Development of method for design a two-level active shielding system for an industrial frequency magnetic field based on a quasi-static model of a magnetic field generated by power line wires and compensating windings of an active shielding system, including coarse open and precise closed control.* ***Methodology.*** *At the first level rough control of the magnetic field in open-loop form is carried out based on a quasi-static model of a magnetic field generated by power line wires and compensating windings of an active shielding system. This design calculated based on the finite element calculations system COMSOL Multiphysics. At the second level, a stabilizing accurate control of the magnetic field is implemented in the form of a dynamic closed system containing, in addition plant, also power amplifiers and measuring devices of the system. This design calculated based on the calculations system MATLAB.* ***Results.*** *The results of theoretical and experimental studies of optimal two-level active shielding system of magnetic field in residential building from power transmission line with a «Barrel» type arrangement of wires by means of active canceling with single compensating winding are presented.* ***Originality.*** *For the first time, the method for design a two-level active shielding system for an power frequency magnetic field based on a quasi-static model of a magnetic field generated by power line wires and compensating windings of an active shielding system, including coarse open and precise closed control is developed.* ***Practical value.*** *It is shown the possibility to reduce the level of magnetic field induction in residential building from power transmission line with a «Barrel» type arrangement of wires by means of active canceling with single compensating winding with initial induction of 3.5 µT to a safe level for the population adopted in Europe with an induction of 0.5 µT.* References 53, figures 9.

Key words: **overhead power line, magnetic field, quasi-static model, system of active shielding, computer simulation, experimental research.**

Мета. *Розробка методу проектування дворівневої системи активного екранування для магнітного поля промислової частоти на основі квазістатичної моделі магнітного поля, яке створюється проводами лінії електропередач і компенсаційними обмотками системи активного екранування, включаючи грубе розімкнуте і точне замкнуте управління.* ***Методологія****. На першому рівні програмне керування магнітним полем в розімкнутій формі здійснюється на основі квазістатичної моделі магнітного поля, яке створюється проводами лінії електропередач і компенсаційними обмотками системи активного екранування. Це проектування виконується на основі розрахункової системи скінчених елементів COMSOL Multiphysics. На другому рівні реалізовано стабілізуюче управління магнітним полем в формі динамічної замкнутої системи, що містить, крім об'єкту управління, також підсилювачі потужності та вимірювальні пристрої. Це проектування виконується в розрахунковій системі MATLAB.* ***Результати.*** *Наведено результати теоретичних та експериментальних досліджень оптимальної дворівневої системи активного екранування магнітного поля з однією компенсуючою обмоткою для житлового будинку від дії магнітного поля лінії електропередачі з розташуванням проводів типу «бочка».* ***Оригінальність.*** *Вперше запропоновано метод проектування дворівневої системи активного екранування магнітного поля промислової частоти на основі квазістатичної моделі магнітного поля, яке створюється проводами лінії електропередач і компенсаційними обмотками системи активного екранування, в вигляді грубого розімкненого і точного закинутого управління.* ***Практична цінність****. Показано можливість зниження рівня індукції магнітного поля в житловому будинку від магнітного поля лінії електропередач з розташуванням проводів типу «бочка» за допомогою однієї компенсуючої обмотки, з початкової індукції в 3,5 мкТл до безпечного рівня для населення, який прийнятий в Європі, з індукцією в 0,5 мкТл.* Бібл. 53, рис. 9.

Ключові слова: **повітряна лінія електропередачі, магнітне поле, квазістатична модель, система активного екранування, комп'ютерне моделювання, експериментальні дослідження.**

Introduction. The constantly accelerating technological progress in energy and communications means that our environment is becoming more and more saturated with electromagnetic waves of various spectra, which can threaten human health. The main cause for concern is the possibility that chronic exposure to low-level non-ionizing radiation can lead to long-term effects such as cancer or degenerative diseases of the immune and nervous systems [1-3].

Therefore in recent years, the terms «electromagnetic ecology», «electromagnetic pollution of the environment» have become firmly established in the topics of scientific publications, scientific conferences, and public hearings and in the controversy of social networks. These terms reflect the awareness of the fact that such presence poses a threat to human health. Such risks of prolonged exposure to an electromagnetic field on the human body are assessed by the World Health Organization and the International Agency for Research on Cancer [1-3].

The most negative impact on the residential environment is provided by overhead power lines that cover large residential and populated areas. They are densely distributed in the modern environment of long-term human stay in residential, industrial and public buildings and in the residential area. Overhead power lines generate industrial frequency magnetic field (MF) inside residential buildings located near power lines, the level of which is often 3-5 times higher than the norms for safe living in the level of the magnetic field adopted in Europe [4-6].

Prolonged exposure of the population to even weak levels of the industrial frequency magnetic field leads to an increased level of cancer in the population living in residential buildings near power lines. The creation of methods and means of normalizing the level of the electromagnetic field in existing residential areas near power lines without evicting the population or decommissioning existing electrical networks determines the economic significance of such studies. Therefore, all over the world, methods are being intensively developed to reduce the level of the magnetic field in existing residential buildings located near power lines to a safe level for the population to live in it [7-23].

The magnetic field active shielding system is an automatic control system, with the help of which a compensating magnetic field is automatically formed, directed against the original magnetic field, which needs to be compensated [24-28]. All fundamental results of the theory of automatic control systems are obtained on the basis of mathematical models of controlled processes in the form of systems of ordinary differential equations [29-33]. Analysis and synthesis of control systems for objects, given in the form of systems of differential equations, is a purely mathematical problem based on the structure of solving differential equations in an analytical form, or on numerical integration methods [34-38].

The cornerstone of the theory of automatic control is to obtain the time dependences of the parameters that determine the state of the control object. In the most general case, mathematical models of control objects can consist of a composition of subsystems of ordinary differential equations and partial differential equations [39-43].

Mathematical modeling of an electromagnetic field reduced to solving a boundary value problem for the system of Maxwell's equations [6]. Maxwell's equations are a system of partial differential equations. When modeling the electromagnetic field of power frequency, a quasi-stationary magnetic field is used, which at each moment of time is completely determined by the distribution of electric currents at the same moment of time and can be found from this distribution in the same way as it is done in magnetostatics.

The task of synthesizing a magnetic field control system is usually complicated by significant uncertainties in the mathematical model of the control object [34-37]. Due to objective circumstances, such as the inaccuracy of the first level model, unmeasured external and internal disturbances, the actual values of the output coordinates will differ from the calculated ones [44-47]. In this regard, we will consider design of two-level magnetic field control system.

At the first level, rough control of the magnetic field is carried out on the basis of a mathematical model of the first approximation. At the second level, a stabilizing accurate of the magnetic field is implemented, which aims to eliminate errors in the output coordinates due to the inaccuracy of the mathematical model of the first level.

In this regard, we will consider a two-level system of active shielding of the industrial frequency magnetic field based on a quasi-static model of the industrial frequency magnetic field generated by power line wires and compensating windings of the active shielding system.

The aim of the work is to develop a method for design a two-level active shielding system for an power frequency magnetic field based on a quasi-static model of a magnetic field generated by power line wires and compensating windings of an active shielding system, and including rough open-loop and accurate closed-loop control.

Quasi-static model of a magnetic field. Mathematical modeling of an electromagnetic field in general terms can be reduced to solving a boundary value problem for Maxwell partial differential equations system [6]

$$\mathrm{rot}\,\boldsymbol{H} = \boldsymbol{j} + \partial_t \boldsymbol{D} + \boldsymbol{j}_{ex}\,; \tag{1}$$

$$\mathrm{rot}\,\boldsymbol{E} = -\partial_t \boldsymbol{B}\,, \tag{2}$$

where $\boldsymbol{E}$ is the electric field strength, $\boldsymbol{H}$ is the magnetic field strength, $\boldsymbol{D}$ and $\boldsymbol{B}$ are the electric and magnetic induction vectors, $\boldsymbol{j}$ – conduction current density, $\boldsymbol{j}_{ex}$ – density of extraneous currents created by sources outside the area under consideration.

The first equation expresses the generalized Ampere law, which states that the total current density is a vortex of magnetic field strength. The second equation contains a differential formulation of Faraday law that the change in time of magnetic induction generates a vortex electric field.

In particular, the magnetic field induction in the immediate vicinity of the wires depends on two spatial variables and changes harmoniously with time and therefore satisfies the second-order elliptic equation

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial \boldsymbol{B}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial \boldsymbol{B}}{\partial y}\right) - \left(\mathrm{j}\omega\sigma - \omega^2\varepsilon\right)\boldsymbol{B} = 0\,, \tag{3}$$

where μ – relative magnetic permeability, ω – circular frequency of the electromagnetic field, σ – electrical conductivity, ε – relative dielectric constant.

An intermediate position between a constant field and a rapidly changing field is occupied by the so-called quasi-stationary field, which is of particular importance in technical applications. A quasi-stationary field is such an electromagnetic field, in the study of which displacement currents can be neglected in comparison with conduction currents. Maxwell equations for a quasi-stationary field are

$$\mathrm{rot}\,\boldsymbol{H} = \boldsymbol{j} + \boldsymbol{j}_{ex}\,; \tag{4}$$

$$\mathrm{rot}\,\boldsymbol{E} = -\partial_t \boldsymbol{B}\,. \tag{5}$$

It follows from the first equation of this approximation that the quasi-stationary magnetic field at each given moment of time is completely determined by the distribution of electric currents at the same moment of time and can be found from this distribution in exactly the same way as it is done in magnetostatics.

To assess the impact of the magnetic field of power lines on the environment, most calculations were performed [33-41] based on the Biot-Savart-Laplace's law for elementary current

$$\mathrm{d}\boldsymbol{H}(t) = \frac{I(t)}{4\pi\boldsymbol{R}^3}(\mathrm{d}l \times \boldsymbol{R})\,, \tag{6}$$

where the vector $\boldsymbol{R}$ is directed from an elementary segment dl with a total current $I(t)$ to the observation point $P(x, y, z)$. Then the total field strength vector is equal to:

$$\boldsymbol{H}(P,t) = \frac{I(t)}{4\pi}\int_L \frac{(\mathrm{d}l \times \boldsymbol{R})}{\boldsymbol{R}^3}. \tag{7}$$

This formula is widely used to calculate the magnetic field of air power transmission lines instead of Maxwell equations system.

Thus, the dependence of the magnitude of the MF intensity on the current is static and is described by (7).

In conclusion, we give one more form of writing a quasi-stationary model of an electromagnetic field those changes in time according to a sinusoidal law. The basic equations and methods for their solution can be significantly simplified by excluding from consideration one of the independent variables – time [6]. When analyzing such fields, a symbolic method is used and harmonically changing quantities are written in complex form

$$I(x,t) = A(x)e^{j\omega t}\,, \qquad (8)$$

where $A(x)$ is the field amplitude.

First level control system synthesis. The block diagram of a two-level control system is shown in Fig. 1.

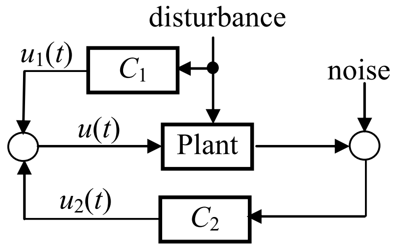

Fig. 1. The block diagram of a two-level control system

At the first level, program controller C_1 in the form of an open loop rough control u_1 is carried out on the basis of a quasi-static mathematical model of the first approximation. At the second level, a stabilizing accurate controller C_2 is implemented in the form of a closed loop control u_2 based on the equations of the dynamics of a closed system, taking into account models of actuating and measuring devices, disturbances and measurement noise, and aimed at eliminating errors in the output coordinates due to the inaccuracy of the mathematical model of the first level.

The magnetic field generated by the power line must be reduced to a safe level. With active shielding with help compensation windings, it is necessary to generate a magnetic field directed against the original MF generated by the power transmission line. The task of the active shielding system design is to calculate the coordinates of the spatial arrangement of the compensating windings, as well as the magnitudes of currents and their phases in the compensating windings.

We set the currents amplitude A_i and phases φ_i of power frequency ω, wires currents power lines. Then we set wires currents in power lines in a complex form

$$I_i(t) = A_i \exp j(\omega t + \varphi_i)\,. \qquad (9)$$

The magnitude of the currents of power lines do not remain constant and have daily, weekly, seasonal and annual fluctuations. Moreover, the magnetic field generated by multi-circuit transmission lines and groups of transmission lines, when changing currents, changes not only the intensity, but also the spatio-temporal characteristic. Therefore, we introduce the vector $\boldsymbol{\delta}$ of uncertainties of the mathematical model of the magnetic field. Then, for given currents (9) of the wires of a power transmission line or a group of power lines the vector $\boldsymbol{B}_L(Q_i,\boldsymbol{\delta},t)$ of the magnetic field generated by all power lines wires $\boldsymbol{B}_{Li}(\boldsymbol{Q}_i,\boldsymbol{\delta},t)$ in point Q_i of the shielding space calculated based on Biot-Savart's law (8)

$$\boldsymbol{B}_L(Q_i,\boldsymbol{\delta},t) = \sum \boldsymbol{B}_l(Q_i,\boldsymbol{\delta},t)\,. \qquad (10)$$

Let's set the vector $\boldsymbol{X}_1$ of initial geometric values of the dimensions of the compensating windings of active shielding, as well as the currents amplitude A_{ai} and phases φ_{ai} in the compensating windings. We set the currents in the compensating windings wires in a complex form

$$I_{ai}(t) = A_{ai} \exp j(\omega t + \varphi_{wi})\,. \qquad (11)$$

Then the vector $\boldsymbol{B}_1(Q_i,\boldsymbol{X}_1,t)$ of the magnetic field generated by all compensating windings wires of active shielding $\boldsymbol{B}_{1i}(Q_i,\boldsymbol{X}_1,t)$ in point Q_i of the shielding space can also calculated based Biot-Savart's law

$$\boldsymbol{B}_1(Q_i,\boldsymbol{X}_1,t) = \sum \boldsymbol{B}_{1i}(Q_i,\boldsymbol{X}_1,t)\,. \qquad (12).$$

Then the vector $\boldsymbol{B}_{R1}(Q_i,\boldsymbol{X}_1,\boldsymbol{\delta},t)$ of the resulting magnetic field generated by power lines and only windings of the first level active shielding system calculated as sum

$$\boldsymbol{B}_{R1}(Q_i,\boldsymbol{X}_1,\boldsymbol{\delta},t) = \boldsymbol{B}_L(Q_i,\boldsymbol{\delta},t) + \boldsymbol{B}_1(Q_i,\boldsymbol{X}_1,t)\,. \qquad (13)$$

Sanitary norms usually limit the value $\boldsymbol{B}_{R1}(Q_i,\boldsymbol{X}_1,\boldsymbol{\delta})$ of the effective value of the magnetic field induction, which determined by the vector of the instantaneous value $\boldsymbol{B}_{R1}(Q_i,\boldsymbol{X}_1,\boldsymbol{\delta},t)$ of the magnetic field induction

$$\boldsymbol{B}_{RI}(Q_i,\boldsymbol{X}_1,\boldsymbol{\delta}) = \frac{\sqrt{2}}{2}\sqrt{\frac{1}{T}\int_0^T \left|\boldsymbol{B}_{R1}(Q_i,\boldsymbol{X}_1,\boldsymbol{\delta},t)\right|^2 dt}\,. \qquad (14)$$

Often they also limit the semi-major axis of the ellipsoid of rotation of the magnetic field induction vector

$$\boldsymbol{B}_{RI}(Q_i,\boldsymbol{X}_1,\boldsymbol{\delta}) = \frac{\sqrt{2}}{2}\max_{0\le t\le T}\left|\boldsymbol{B}_{RI}(Q_i,\boldsymbol{X}_1,\boldsymbol{\delta},t)\right|\,. \qquad (15)$$

Then the problem of designing a first level control system is reduced to computing the solution of the vector game

$$\boldsymbol{B}_{R1}(\boldsymbol{X}_1,\boldsymbol{\delta}) = \langle \boldsymbol{B}_{R1}(Q_i,\boldsymbol{X}_1,\boldsymbol{\delta})\rangle \qquad (16)$$

The components of the game payoff vector $\boldsymbol{B}_{R1}(\boldsymbol{X}_1,\boldsymbol{\delta})$ are the effective values $\boldsymbol{B}_{R1}(Q_i,\boldsymbol{X}_1,\boldsymbol{\delta})$ of the induction of the resulting magnetic field at all considered points Q_i in the shielding space.

In this vector game it is necessary to find the minimum of the game payoff vector (16) by the vector $\boldsymbol{X}_1$, but the maximum of the same game payoff vector (16) by the vector $\boldsymbol{\delta}$.

At the same time, naturally, it is necessary to take into account constraints on the vector $\boldsymbol{X}$ desired parameters of a combined shield in the form of vector inequality and, possibly, vector equality

$$\boldsymbol{G}(\boldsymbol{X}_1) \le \boldsymbol{G}_{\max}\,, \quad \boldsymbol{H}(\boldsymbol{X}_1) = 0\,. \qquad (17)$$

Note that the components of the vector game (16) and vector constraints (17) are the nonlinear functions of the vector of the required parameters [5, 6] and calculated based on the finite element calculations system COMSOL Multiphysics.

Second level control system synthesis. Consider the structure of the second level active shielding system in the form of a dynamic closed system containing, in addition plant, also power amplifiers and measuring devices of the system. In the zone of active shielding of the magnetic field, m sources of the magnetic field – magnetic executive bodies – are installed. Let's introduce a n – dimensional control vector $\boldsymbol{u}_P(t)$, the m components of which are the currents $\boldsymbol{I}_w(t)$ in the control windings. Let's introduce an n – dimensional state vector $\boldsymbol{x}_P(t)$ whose components include currents $I_w(t)$ in the windings of magnetic field sources. Then the state equation of such magnetic field sources can be written in the standard form

$$\boldsymbol{x}_p(t+1) = A_p\boldsymbol{x}_p(t) + B_p\boldsymbol{u}_P(t)\,, \qquad (18)$$

$$\boldsymbol{I}_w(t) = C_p\boldsymbol{x}_p(t)\,, \qquad (19)$$

in which the state A_P, control B_P and output C_P matrices of magnetic field sources as plant.

This differential equation describes the dynamics of only the actual windings and their power sources as plant.

Let's write down the differential equation of state of discrete PID controllers, the input of which is the $\boldsymbol{u}_S(t)$ of measured magnetic field induction components, and the output $\boldsymbol{u}_P(t)$ is the vector of closed-loop control of magnetic executive bodies in the following form

$$\boldsymbol{x}_c(t+1) = A_c \boldsymbol{x}_C(t) + B_C \boldsymbol{u}_S(t); \tag{20}$$

$$\boldsymbol{u}_P(t) = C_C \boldsymbol{x}_C(t), \tag{21}$$

in which the state A_C, control B_C and output C_C matrices of PID controllers.

To design second level active shielding system, it is necessary to have magnetic field measuring devices – magnetometers installed at certain points in space to measure the magnetic field $\boldsymbol{H}_S(t)$ created both by the output transmission line and by the executive windings of the active shielding system. Let's form a vector $\boldsymbol{u}_S(t)$ of measured components at the moment of time t at the points P_j of installation of magnetometers in the following form

$$\boldsymbol{x}_s(t+1) = A_S \boldsymbol{x}_S(t) + B_S \boldsymbol{H}_S(t); \tag{22}$$

$$\boldsymbol{u}_S(t) = C_S \boldsymbol{x}_S(t) + \boldsymbol{w}(t), \tag{23}$$

in which the state A_S, control B_S and output C_S matrices of magnetometers.

Let's introduce the vector $\boldsymbol{X}_2 = \{A_C, B_C, C_C\}$ of sought parameters, the components of which are the sought elements of the state A_C, control B_C and output C_C matrices of PID controllers of second level active shielding system.

Then for the current $I_w(t)$ calculated by (19) in the windings the vector $\boldsymbol{B}_2(Q_i,\boldsymbol{X}_2,t)$ of the magnetic field generated by all compensating windings wires of second level active shielding $\boldsymbol{B}_{2i}(Q_i,\boldsymbol{X}_2,t)$ in point Q_i of the shielding space can also calculated based Biot-Savart's law

$$\boldsymbol{B}_2(Q_i, \boldsymbol{X}_2, t) = \sum \boldsymbol{B}_{2i}(Q_i, \boldsymbol{X}_2, t). \tag{24}$$

Then the vector $\boldsymbol{B}_R(Q_i,\boldsymbol{X}_1,\boldsymbol{X}_2,\boldsymbol{\delta},t)$ of the resulting magnetic field generated by power lines and windings of both first and second level active shielding system calculated as sum

$$\begin{aligned} \boldsymbol{B}_R(Q_i, \boldsymbol{X}_1, \boldsymbol{X}_2, \boldsymbol{\delta}, t) &= \boldsymbol{B}_L(Q_i, \boldsymbol{\delta}, t) + \ldots \\ \ldots &+ \boldsymbol{B}_1(Q_i, \boldsymbol{X}_1, t) + \boldsymbol{B}_2(Q_i, \boldsymbol{X}_2, t). \end{aligned} \tag{25}$$

Note that equations (18) – (25) describe the dynamics of a closed second level active shielding system.

Then the problem of designing a second level control system is reduced to computing the solution of the vector game

$$\boldsymbol{B}_R(\boldsymbol{X}_2, \boldsymbol{\delta}) = \langle \boldsymbol{B}_R(Q_i, \boldsymbol{X}_1^*, \boldsymbol{X}_2, \boldsymbol{\delta}) \rangle. \tag{26}$$

The components of the game payoff vector $\boldsymbol{B}_R(\boldsymbol{X}_2,\boldsymbol{\delta},t)$ are the effective values $\boldsymbol{B}_R(Q_i, \boldsymbol{X}_1^*, \boldsymbol{X}_2, \boldsymbol{\delta})$ of the induction of the resulting magnetic field at all considered points Q_i in the shielding space calculated for the optimal value of the vector $\boldsymbol{X}_1^*$ of parameters of first level active shielding system.

Then the synthesis of the two level system of active shielding of the magnetic field, which includes open and closed control circuits, is reduced to finding the $\boldsymbol{X}_1$ and the $\boldsymbol{X}_2$ of the parameters of the controllers.

Problem solving algorithm. A feature of the solution of the considered multi-criteria problem is inconsistency of local criteria to each other, which prevents the simultaneous optimization in general by all criteria at the same time [44]. This is due to the fact that minimizing the induction at one point, for example, located in the center of the screening space, leads to an increase in the induction at the points located closer to the power line due to overcompensation of the original magnetic field, and at the same time leads to an increase in the induction of the resulting magnetic field at points located farther than the power line due to undercompensation of the original magnetic field.

This means that one goal cannot be optimized at the expense of another goal. To solve the problems of multicriteria optimization, various strategies have been developed and each approach has its own pros and cons, and there is no single best option for solutions to multi-criteria optimization in the general case. The simplest method for solving the problem of multi-objective optimization is to form a composite objective function as a weighted sum of goals, where the weight for goals is proportional to the preference for this local criterion. Scalarization of the target vector into one component objective function transforms the multiobjective optimization problem into a single optimization goal.

Usually, the maximum values of partial criteria are known, which makes it possible to perform normalization. In this case, the normalized partial criteria are in the range $0 \le \boldsymbol{B}_{RN}(Q_i,\boldsymbol{X}) \le 1$. Approximation of the normalized value of the i–th particular criterion to unity corresponds to a tense situation. If the value of the normalized value of the particular criterion approaches zero, then this corresponds to a calm situation. To solve this problem of multicriteria optimization, the simplest non-linear trade-off scheme is used, in which the original multi-criteria problem is reduced to a single-criteria

$$\vec{\boldsymbol{X}}^* = \arg\min_{\vec{X}} \sum_{i=1}^{J} \alpha_i [1 - \boldsymbol{B}_{RN}(Q_i, \boldsymbol{X})]^{-1}, \tag{27}$$

where α_i are weight coefficients that characterize the importance of particular criteria and determine the preference for individual criteria by the decision maker. Naturally, such a formalization of the solution of the problem of multi-criteria optimization by reducing to a single-criteria problem allows one to reasonably choose one single point from the area of compromises – the Pareto area. However, this «single» point can be further tested in order to further improve the trade-off scheme from the point of view of the decision maker.

Note, that such a nonlinear scheme of trade-offs actually corresponds to the penalty function method with an internal point, since when the criterion $\boldsymbol{B}(Q_i,\boldsymbol{X})$ approaches unity, i.e. in a tense situation, scalar optimization is actually performed only according to this tense particular criterion, and the remaining criteria with a calm situation are practically not taken into account during optimization.

Such a non-linear trade-off scheme allows you to choose criteria in accordance with the intensity of the situation. If any criterion comes close to its limit value, then its normalized value approaches one. Then this nonlinear compromise scheme, in fact, with the help of a scalar criterion, reduces the problem of minimizing the sum of criteria to minimizing this one criterion, according to which there is a tense situation. If, according to other criteria, the situation is calm and their relative values are far from unity, then such a non-linear compromise scheme operates similarly to a simple linear compromise scheme.

Thus, with the help of this non-linear scheme of compromises, in fact, the tension of the situation according to individual criteria is a priori introduced into the scalar criterion. It can be shown that this non-linear compromise scheme satisfies the Pareto-optimality condition, i.e. using this scheme, it is possible to determine a point from the region of unimprovable solutions. When such a composite objective function optimized, in most cases you can get one concrete compromise solution. This processing procedure multiobjective optimization problems are simple, but relatively subjective. This procedure is based on preferences multipurpose optimization.

The second approach is to define the entire set solutions that are not dominated with respect to each another. This set is known as the Pareto optimal set. Bye moving from one Pareto solution to another, always a certain number of victims in one or more goals to achieve a certain gain in other(s). Pareto-optimal solution sets are often preferred over single solutions because they can be practical when consideration of real life problems. Pareto set size usually increases with an increase in the number goals. The result obtained preference-based strategy largely depends on the relative a preference vector used in the formation of a composite function. Changing this preference vector leads to another compromise solution. On the other hand, the ideal multipurpose the optimization procedure is less subjective. The main task in this approach is to find as many different compromises as possible solutions as far as possible.

Let's consider the method of solving the formulated problem. In order to correctly solve the problem of multi-criteria optimization, in addition to the vector optimization criterion and constraints, it is also necessary to have information about the binary relations of preference of local solutions to each other. The basis of this formal approach is the construction of areas of Pareto-optimal solutions. This approach makes it possible to significantly narrow the range of possible optimal solutions to the initial multi-criteria optimization problem and, therefore, to reduce the labor intensity of the person making the decision regarding the selection of a single variant of the optimal solution.

The task of finding a local minimum at one point of the considered space is, as a rule, multi-extreme, containing local minima and maxima, therefore, it is advisable to use stochastic multi-agent optimization algorithms for its solution. Consider the algorithm for finding the set of Pareto-optimal solutions of multi-criteria nonlinear programming problems based on stochastic multi-agent optimization.

To date, a large number of Particle Swarm Optimization (PSO) algorithms have been developed – PSO algorithms based on the idea of the collective intelligence of a particle swarm, such as the gbest PSO and lbest PSO algorithms [48-50]. The application of stochastic multi-agent optimization methods for solving multi-criteria problems today causes certain difficulties and this direction continues to develop intensively.

To solve the original multi-criteria problem of nonlinear programming with constraints, we will build a stochastic multi-agent optimization algorithm based on a set of particle swarms, the number of which is equal to the number of components of the vector optimization criterion. In the standard particle swarm optimization algorithm, particle velocities change according to linear laws. In order to increase the speed of finding a global solution, special nonlinear algorithms of stochastic multi-agent optimization have recently become widespread, in which the movement of particle i swarm j is described by the following expressions

$$\begin{aligned} v_{ij}(t+1) &= w_j v_{ij}(t) + c_{1j} r_{1j}(t) H\left(p_{1j} - \varepsilon_{1j}(t)\right) \times \ldots \\ &\ldots \times \left[y_{ij}(t) - x_{ij}(t)\right] + c_{2j} r_{2j}(t) H\left(p_{2j} - \varepsilon_{2j}(t)\right) \times \ldots \\ &\ldots \times \left[y_j^*(t) - x_{ij}(t)\right]; \end{aligned} \tag{28}$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1), \tag{29}$$

where, are the position $x_{ij}(t)$ and speed $v_{ij}(t)$ of the particle i of the swarm j; c_1 and c_2 – positive constants that determine the weights of the cognitive and social components of the speed of particle movement; $r_{1j}(t)$ and $r_{2j}(t)$ are random numbers from the range [0, 1], which determine the stochastic component of the particle velocity component. Here, $y_{ij}(t)$ and y_j^* – the best local-lbest and global-gbest positions of that particle i are found, respectively, only by one particle i and by all particles i of that swarm j. The use of the inertia coefficient w_j allows to improve the quality of the optimization process.

The Heavyside function H is used as a function of switching the movement of the time-stick in accordance with the local $y_{ij}(t)$ and global $y_j^*(t)$ optimum. Parameters of switching the cognitive p_{1j} and social p_{2j} components of the speed of particle movement in accordance with the local and global optimum; random numbers $\varepsilon_{1j}(t)$ and $\varepsilon_{2j}(t)$ determine the parameters of switching the movement of the particle according to the local and global optimum. If $p_{1j}<\varepsilon_{1j}(t)$ and $p_{2j}<\varepsilon_{2j}(t)$, then the speed of movement of particle i swarm j does not change at the step t and the particle moves in the same direction as in the previous optimization step.

With the help of individual swarms j, optimization problems of scalar criteria $\boldsymbol{B}(\boldsymbol{X},P_j)$, which are components of vector optimization criteria, are solved. To find a global solution to the original multi-criteria problem, individual swarms exchange information among themselves during the search for optimal solutions of local criteria. At the same time, information about the global optimum obtained by the particles of another swarm is used to calculate the speed of movement of the particles of one swarm, which allows all potential Pareto-optimal solutions to be identified [51-53].

For this purpose, at each step t of the movement of particle i swarm j, the functions of advantages of local solutions obtained by all swarms are used. The solution $\boldsymbol{X}_j^*(t)$ obtained during the optimization of the objective function $\boldsymbol{B}(\boldsymbol{X}(t),P_k)$ using the swarm k is $\boldsymbol{X}_j^*(t) \succ \boldsymbol{X}_k^*(t)$ better in relation to the solution obtained during the optimization of the objective function using the swarm j, i.e., if the condition is fulfilled

$$\max_{i=1,m} \boldsymbol{B}\left(P_i, \boldsymbol{X}_j^*(t)\right) < \max_{i=1,m} \boldsymbol{B}\left(P_i, \boldsymbol{X}_k^*(t)\right). \qquad (30)$$

At the same time, the global solution $\boldsymbol{X}_k^*(t)$ obtained by the swarm k is used as the global optimal solution $\boldsymbol{X}_j^*(t)$ of the swarm j, which is better than the global solution $\boldsymbol{X}_k^*(t)$ of the swarm k on the basis of the weight ratio.

In fact, this approach implements the basic idea of the method of successive narrowing of the area of rade-offs – from the initial set of possible solutions, based on information about the relative importance of local solutions, all Pareto-optimal solutions that cannot be chosen according to the available information about the attitude of superiority. The deletion is carried out until a globally optimal solution is obtained. As a result of applying such an approach, no potentially optimal solution will be removed at each narrowing step.

Simulation results. Let us consider the results of the design of a two-level system of active shielding of the magnetic field generated by a double-circuit power line in a residential building, as shown in Fig. 2.

Fig. 2. Residential building closed to double-circuit power line

Figure 3 shows the scheme of the two-level active shielding system design.

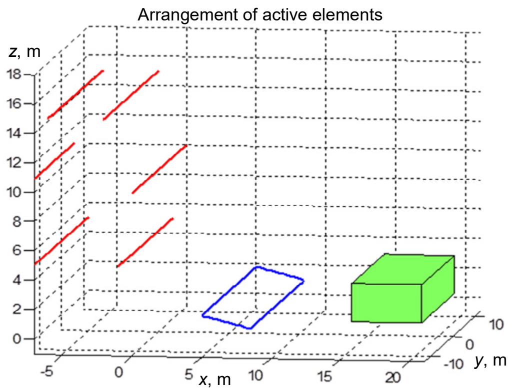

Fig. 3. Scheme of the two-level active shielding system design

Figure 4 shows the dependences of the initial and resulting magnetic field. With the help of the system, the level of the magnetic field does not exceed the level of 0.5 μT, which is accepted as a safe level of the magnetic field in Europe.

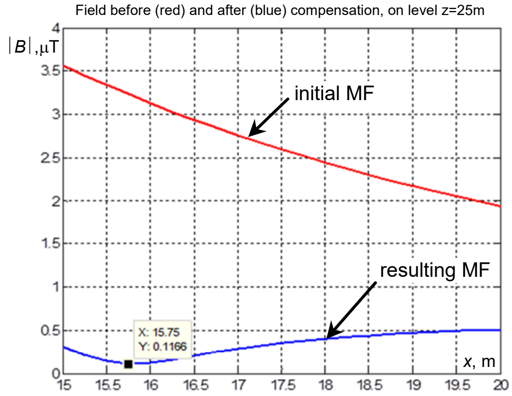

Fig. 4. Dependences of the initial and resulting magnetic field

Figure 5 shows the dependences of the spatio-temporal characteristic of the initial and resulting magnetic field and the magnetic field generated only by the compensation winding.

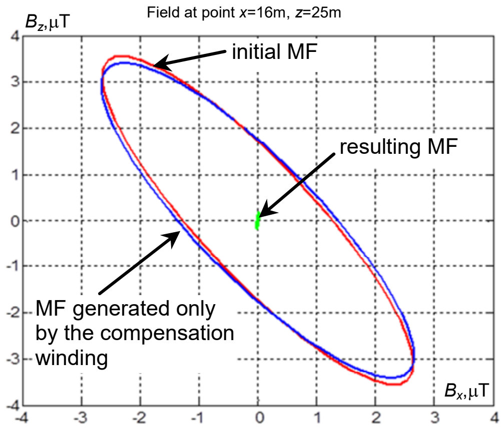

Fig. 5. Dependences of the spatio-temporal characteristic of the initial and resulting magnetic field and the magnetic field generated only by the compensation winding

Results of experimental studies. Let us now consider the results of experimental studies of the system. On Fig. 6 shows the compensation winding of the experimental setup.

Fig. 6. Compensation winding of the experimental setup

On Fig. 7 shows the control system of the experimental setup.

On Fig. 8 shows the experimental spatio-temporal characteristic of the initial magnetic field.

On Fig. 9 shows the experimental spatio-temporal characteristic of the resulting magnetic field. On the basis of experimental studies of the experimental installation of a two-level active shielding system, it was found that the shielding factor is more than 7 units.

Fig. 7. Active shielding system of the experimental setup

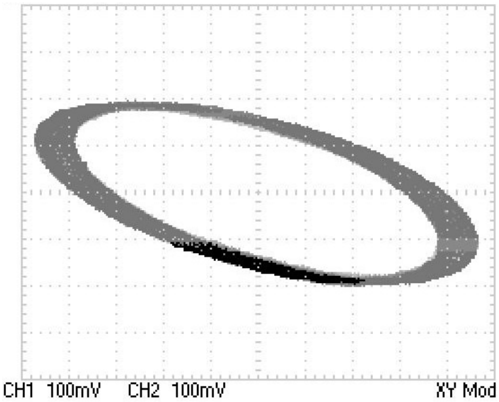

Fig. 8. Experimental spatio-temporal characteristic of the initial magnetic field

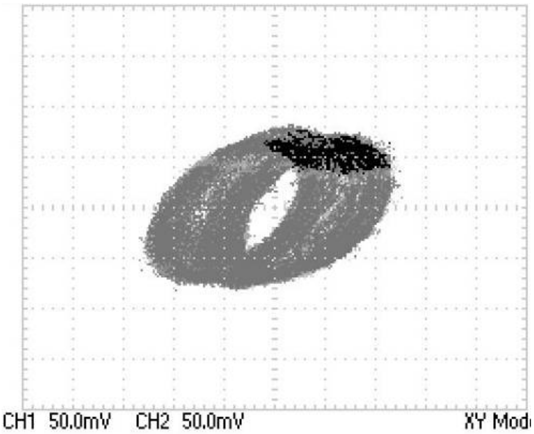

Fig. 9. Experimental spatio-temporal characteristic of the resulting magnetic field

If it is possible to measure the current of the current line of three-phase power lines or to directly measure the induction of the magnetic field near the current line, then an open system of active shielding can be built on the basis of these measurements.

Conclusions.

1. At the first level rough control of the magnetic field in open-loop form is carried out based on a quasi-static model of a magnetic field generated by power line wires and compensating windings of an active shielding system. This design calculated based on the finite element calculations system COMSOL Multiphysics.

2. At the second level, a stabilizing accurate control of the magnetic field is implemented in the form of a dynamic closed system containing, in addition plant, also power amplifiers and measuring devices of the system. This design calculated based on the calculations system MATLAB.

3. Design both first and second level control according to the developed method reduced to computing the solution of vector multi-criteria two-player zero-sum antagonistic game based on binary preference relations. The payoff game vector and constraints calculation based on quasi-static model of a magnetic field. These solutions calculated from sat of Pareto-optimal solutions based on binary preferences based on stochastic nonlinear Archimedes algorithms.

4. Two-level control system under consideration is a system with two degrees of freedom, which combines both open-loop and closed-loop control. However, in contrast to the classical synthesis of robust control of a system with two degrees of freedom, in the developed method, the synthesis of open-loop rough control is performed on the basis of a quasi-static model of the magnetic field. The synthesis of a closed-loop accurate control is carried out on the basis of the equations of the dynamics of a closed system, taking into account models of actuating and measuring devices, disturbances and measurement noise.

5. Using calculated optimal two-level active shielding system made it possible to reduce the level of magnetic field in residential building from power transmission line with a «Barrel» type arrangement of wires by means of active canceling with single compensating winding with initial induction of 3.5 µT to a safe level for the population adopted in Europe with an induction of 0.5 µT.

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Conflict of interest. The authors declare that they have no conflicts of interest.

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