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The method for design of combined electromagnetic shield for overhead power lines magnetic field

Aim. *Development of the method of designing a combined electromagnetic shield, consisting of active and passive parts, to improve the effectiveness of reduction of industrial frequency magnetic field created by two-circuit overhead power lines in residential buildings.* ***Methodology****. The problem of design of combined electromagnetic shield including robust system of active shielding and electromagnetic passive shield of initial magnetic field solved based on of the multi-criteria two-player antagonistic game. The game payoff vector calculated based on the finite element calculations system COMSOL Muliphysics. The game solution calculated based on the particles multiswarm optimization algorithms. During the design of combined electromagnetic shields spatial location coordinates of shielding winding, the currents and phases in the shielding winding of active shielding, geometric dimensions and thickness of the electromagnetic passive shield are calculated.* ***Results.*** *The results of theoretical and experimental studies of combined electromagnetic passive and active shielding of magnetic field in residential building from power transmission line with a «Barrel» type arrangement of wires presented.* ***Originality****. For the first time the method of designing a combined electromagnetic shield, consisting of active and passive parts, for more effective reduction of the magnetic field of industrial frequency created by two-circuit overhead power lines in residential buildings is developed.* ***Practical value****. Based on results of calculated and experimental study the shielding efficiency of the initial magnetic field determined that shielding factors whith only electromagnetic passive shield is more 2 units, whith only active shield is more 4 units and with combined electromagnetic passive and active shield is more 10 units. 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 a combined electromagnetic passive and active shielding with single compensating winding to 0.5 μT level safe for the population.* References 53, figures 15.

Key words: **overhead power line, magnetic field, combined electromagnetic passive and active shielding, computer simulation, experimental research.**

Мета*. Розробка методу проектування комбінованого електромагнітного екрану, що складається з активної та пасивної частин, для підвищення ефективності зниження магнітного поля промислової частоти, створюваного дволанцюговими повітряними лініями електропередачі в житлових будинках.* ***Методологія.*** *Задача проектування комбінованого електромагнітного екрану, що включає робастну систему активного екранування та електромагнітний пасивний екран вихідного магнітного поля, вирішується на основі багатокритеріальної антагоністичної гри двох гравців. Вектор виграшів гри розраховується на основі кінцево-елементної системи обчислень COMSOL Muliphysics. Рішення гри розраховується на основі алгоритмів оптимізації мультироїв частинок. При проектуванні комбінованих електромагнітних екранів розраховуються координати розташування екрануючої обмотки в просторі, струм і фаза в екрануючій обмотці робастної системи активного екранування, та геометричні розміри і товщина електромагнітного пасивного екрану.* ***Результати****. Наведено результати теоретичних та експериментальних досліджень комбінованого електромагнітного пасивного та активного екранування магнітного поля в житловому будинку від дволанцюгової лінії електропередач із розташуванням проводів типу «бочка».* ***Оригінальність****. Вперше розроблено метод проектування комбінованого електромагнітного екрану, що складається з активної та пасивної частин, для підвищення ефективності зниження магнітного поля промислової частоти, створюваного дволанцюговими повітряними лініями електропередачі в житлових будинках.* ***Практична цінність****. За результатами розрахункових та експериментальних досліджень ефективність екранування початкового магнітного поля визначено, що коефіцієнти екранування системи тільки з електромагнітним пасивним екраном дорівнює більше 2 одиниць, тільки з активним екраном дорівнює більше 4 одиниць, а з комбінованим електромагнітним пасивним і активним екраном дорівнює більше 10 одиниць. Показано можливість зниження рівня індукції магнітного поля в житловому будинку від дволанцюгової лінії електропередач із розташуванням проводів типу «бочка» за допомогою комбінованого електромагнітного пасивного та активного екранування з однією компенсуючою обмоткою до безпечного для населення рівня в 0,5 мкТл.* Бібл. 53, рис. 15.

Ключові слова: **повітряна лінія електропередачі, магнітне поле, комбіноване електромагнітне пасивне та активне екранування, комп'ютерне моделювання, експериментальні дослідження.**

Introduction. 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 [1-3]. 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, methods are being intensively developed all over the world to reduce the level of the magnetic field (MF) in existing residential buildings located near power lines to a safe level for the population to live in it [4-7].

To reduce the magnetic field inside residential premises, it is technically easiest to use passive shielding. The principle of operation of the electromagnetic shield can be described as follows [8-15]: under the action of the primary MF, conduction currents are induced in the shield; these currents create a secondary field; from the addition of the primary field with the secondary, the resulting field is formed, which is weaker than the primary in the protected area. Therefore, for the manufacture of electromagnetic shields, materials with a high electrical conductivity value should be used. The most widely used electromagnetic screens are made of aluminum, the cost of which is relatively low. However, the cost of such passive screens, especially when screening large volumes of residential premises, is the main limitation of the use of such screens, especially when using mu-metal passive screens. To increase the shielding efficiency, multilayer passive shields are widely used, consisting of several layers of conductive and ferromagnetic shields. Such screens are widely used for shielding the magnetic field in magnetically clean rooms together with active screens.

For shielding large volumes, it is economically most expedient to use active shields [16-23]. A feature of the use of active screens is the need to provide an active screening system and constant power consumption during the operation of the system. To save energy consumption, the active shielding system can only be switched on when there are people in the living space. Therefore, when designing shielding systems for residential premises, it can often be the most effective option to use combined shielding of the initial magnetic field, including an active shielding system and passive shielding.

Such combined screens are widely used in world practice [16]. On Fig. 1 show a room located near power lines. The main shielding effect is provided by an active shielding system with one compensation winding laid along the building. Additional screening is provided by passive screen sheets laid on the floor.

Fig. 1. The room located near power lines

The aim of the work is development of method of designing a combined electromagnetic shield, consisting of active and passive parts, to improve the effectiveness of reduction of industrial frequency magnetic field created by two-circuit overhead power lines in residential buildings.

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

$$I_i(t) = A_i \exp j(\omega t + \varphi_i). \tag{1}$$

Then the vector $\boldsymbol{B_p}(Q_i,t)$ of the magnetic field generated by all power lines wires in point Q_i of the shielding space can calculated based Biot-Savart law [6].

We set the vector $\boldsymbol{X_a}$ of initial geometric values of the dimensions of the compensating windings, as well as the currents amplitude A_{wi} and phases φ_{wi} in the compensating windings. We set the currents in the compensating windings wires in a complex form

$$I_{wi}(t) = A_{wi} \exp j(\omega t + \varphi_{wi}). \tag{2}$$

Then the vector $\boldsymbol{B_W}(Q_i,\ t)$ of the magnetic field generated by all compensating windings wires in point Q_i of the shielding space can also calculated based Biot-Savart law.

Let us set the vector $\boldsymbol{X_p}$ of initial values of the geometric dimensions, thickness and material of the passive shield. Then for the given geometric dimensions of the power lines wire and the initial values of the geometric dimensions of the compensation winding wires, as well as for the given values of currents and phases in the power lines wires and the initial values of currents and phases in the wires in the compensation windings, as well as for the initial values of the geometric dimensions, thickness and material of the passive screens, the vector $\boldsymbol{B_R}(Q_i,\ t)$ of the rezalting magnetic field induction in the Q_i point of the shielding space can be calculated.

We introduce the vector $\boldsymbol{X}$ of the desired parameters of the problem of designing a combined shield, the components of which are the vector $\boldsymbol{X_a}$ values of the geometric dimensions of the compensation windings, as well as the currents A_{wi} and phases φ_{wi} in the compensation windings, as well as the vector $\boldsymbol{X_p}$ of geometric dimensions, thickness and material of the passive shield.

Let us introduce the vector $\boldsymbol{\delta}$ of the uncertainty parameters of the problem of designing a combined shield, the components of which are inaccurate knowledge of the currents and phases in the wires of the power transmission line, as well as other parameters of the combined shielding system, which, firstly, are initially known inaccurately and, secondly, may change during the operation of the system [24-28].

Then for the given initial values of the $\boldsymbol{X}$ vector of the desired parameters and the vector $\boldsymbol{\delta}$ of the uncertainty parameters of the combined screen design problem, the value $\boldsymbol{B_R}(\boldsymbol{X},\ \boldsymbol{\delta},\ P_i)$ of the magnetic induction at the point P_i of the shielding space calculated based on the finite element calculations system COMSOL Muliphysics. Then the problem of designing a passive screen is reduced to computing the solution of the vector game

$$\boldsymbol{B_R}(\boldsymbol{X},\boldsymbol{\delta}) = \langle B_R(X,\delta,P_1)\rangle. \tag{3}$$

The components of the game payoff vector $\boldsymbol{B_R}(\boldsymbol{X},\ \boldsymbol{\delta})$ are the effective values of the induction of the resulting magnetic field $\boldsymbol{B_R}(\boldsymbol{X},\ \boldsymbol{\delta},\ P_i)$ 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 (11) by the vector $\boldsymbol{X}$, but the maximum of the same vector objective function 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 [29-33]

$$\boldsymbol{G}(\boldsymbol{X}) \le \boldsymbol{G_{max}}, \quad \boldsymbol{H}(\boldsymbol{X}) = 0. \tag{4}$$

Note that the components of the vector game (3) and vector constraints (4) are the nonlinear functions of the vector of the required parameters [5, 6].

The solutions of the vector game (3) subject to constraints (4) are calculated from the Pareto set of optimal solutions based on algorithms particles multiswarm optimization.

Solving problem agorithm. A feature of the problem under consideration is the presence of several conflicting goals. Minimization of the magnetic field at one point leads to an increase in the magnetic field at other points due to undercompensation or overcompensation of the initial magnetic field. Minimax problems are widely used in robust control. If it is necessary to find the minimum in one variable and the maximum in other variables of the same objective function, then the necessary condition for the optimal minimax problem is that the gradient of the objective function in all variables is equal to zero, regardless of whether the target function is minimized or maximized function [34-37].

When solving this minimax problem numerically, in order to find the direction of movement, it is necessary to use the components of the gradient of the objective function for those variables over which the maximization is performed, and it is necessary to use the components of the antigradient (i.e., the gradient taken with the opposite sign) for those variables over which the minimization is performed [38-43].

Recently, in the synthesis of control systems, a game approach has become widespread, which makes it possible to formulate the problem of synthesizing a system for a game. In this case, the area of parameter variations is divided into two sets of friendly $\boldsymbol{X}$ and enemy $\boldsymbol{\delta}$. The goal of the players is to choose such values X at which the value of the optimized quality criterion (3) is minimized, and the task of the opponent is to choose such values of the parameters $\boldsymbol{\delta}$ at which the value of the quality criterion is maximized.

To solve this minimax problem of multi-criteria optimization (3), we use the simplest linear trade-off scheme, in which the original multi-criteria problem was reduced to a single-criteria

$$\boldsymbol{f(X,\delta)} = \sum_{i=1}^{J} \alpha_i \boldsymbol{B_R(X,\delta,}P_I) \tag{5}$$

where α_i are weight coefficients that characterize the importance of particular criteria and determine the preference for individual criteria by the decision maker.

A necessary condition for optimality

$$\boldsymbol{X}^* = \arg\min_X \sum_{i=1}^{J} \alpha_i \boldsymbol{B_R(X,\delta,}P_I); \tag{6}$$

$$\boldsymbol{\delta}^* = \arg\max_\delta \sum_{i=1}^{J} \alpha_i \boldsymbol{B_R(X,\delta,}P_I) \tag{7}$$

is the existence of a saddle point. In which the equality to zero of the gradients of the objective function

$$\nabla_{\boldsymbol{X}} \boldsymbol{f}/_{\boldsymbol{X}=\boldsymbol{X}^*} = 0, \quad \nabla_{\boldsymbol{\delta}} \boldsymbol{f}/_{\boldsymbol{\delta}=\boldsymbol{\delta}^*} = 0. \tag{8}$$

A sufficient condition for the existence of a saddle point is a change in the sign of the gradient $\nabla_X \boldsymbol{f}$ when passing the minimum point from minus to plus, and a change in the signs of the gradient $\nabla_\delta \boldsymbol{f}$ when passing the maximum point from plus to minus [44-47]. These conditions can be formulated as the positive definiteness $\boldsymbol{H_X}>0$ of the matrix of second derivatives – the Hessian matrix with respect to the choice of parameters X, and the negative definiteness $\boldsymbol{H_\delta}\leq 0$ of the Hessian matrix with respect to the parameters $\boldsymbol{\delta}$, i.e. the task becomes much more complicated if the quality criterion is vector $\boldsymbol{B_R(X,\delta)}$.

Note that the quality criterion $\boldsymbol{B_R(X,\delta)}$ usually includes both system state variables or their combination, characterizing the accuracy of the system, and state variables that need to be limited and the control vector is necessarily included. Otherwise, the original problem becomes degenerate and leads to infinite controls. Moreover, the choice of weight matrix functions in the quality criterion when solving specific problems is carried out iteratively by repeatedly solving the original optimization problem for different values of the weight functions until acceptable results are obtained.

In fact, the semantic statement of the problem is reduced to the synthesis of such a system, which provides the minimum value of the error characterizing the accuracy of the system when constraints (4) on the state vector component are met and when constraints on the control vector are met.

Consider the use of penalty (barrier functions) for solving a mathematical programming problem in the presence of restrictions. Let us first consider the application of the interior point method to solve a mathematical programming problem that does not contain restrictions in the form of equalities. Let us assume that near the optimal point, the local optimum conditions are satisfied in the following form

$$\begin{cases} g_i(x) \geq 0,\ i = \overline{1,m}, \\ u_i g_i(x) = r > 0,\ i = \overline{1,m}, \\ u_i \geq 0,\ i = \overline{1,m}, \\ \nabla f(x) - \sum_{i=1}^{m} u_i \nabla g_i(x) = 0. \end{cases} \tag{9}$$

Whence the following equality can be obtained

$$\nabla f(x(r)) - \sum_{i=1}^{m} \frac{r}{g_i(x(r))} \nabla g_i(x(r)) = 0. \tag{10}$$

This equality can be interpreted as a necessary condition for a local optimum in the form of zero gradient, under which the original objective function of the nonlinear programming problem takes the following form

$$L(x,r) = f(x) - r\sum_{i=1}^{m} \ln g_i(x). \tag{11}$$

Similarly, another objective function can be obtained, provided that from the expression

$$\lambda_i g_i(x) = r > 0,\ i = \overline{1,m} \tag{12}$$

for the gradient

$$\nabla f[x(r)] - \sum_{i=1}^{m} \frac{r^2}{g_i^2[x(r)]} \nabla g_i[x(r)] = 0. \tag{13}$$

The objective function $L_1(x, r)$ will take the following form

$$L_1(x,r) = f(x) + r^2 \sum_{i=1}^{m} \frac{1}{g_i(x)}. \tag{14}$$

These objective functions allow us to reduce the initial problem of nonlinear programming in the presence of restrictions to the solution of the problem of unconditional optimization in such a way that when approaching the boundary of the restrictions from the inside, the penalty for violation of the restrictions tends to infinity, which corresponds to the interior point method in the penalty functions algorithm.

Thus the problem of multicriteria synthesis (3) of nonlinear robust control using a linear compromise scheme (5) is reduced to a single-criteria problem of mathematical programming (12). Consider the application of the sequential quadratic programming method to solve this problem. This method and its software implementation were proposed by Schittkowski at the beginning for solving the least squares minimization problem. This method is a combination of the Gauss-Newton method with determining the direction of movement using a quasi-Newtonian algorithm.

Consider first the minimization of the quadratic norm L_2, usually called the unconstrained least squares problem

$$f(x) = \frac{1}{2}\sum_{i=1}^{l} f_i(x)^2. \tag{15}$$

The gradient of this objective function can be represented as follows

$$\nabla f(x) = \nabla F(x) F(x), \tag{16}$$

where the Jacobian $\nabla F(x) = (\nabla f_1(x),..., \nabla f_l(x))$ of this function is denoted and it is assumed that the components of the objective function can be doubly differentiated. Then the matrix of second derivatives of the objective function – the Hesse matrix can be written in the following form

$$\nabla^2 f(x) = \nabla F(x) \nabla F(x)^T + B(x), \tag{17}$$

where

$$B(x) = \sum_{i=1}^{l} f_i(x) \nabla^2 f_i(x) \nabla^2 f_i(x).$$

Then the iterative procedure for choosing the direction $d_k \in R^n$ of motion using the Newton method can be reduced to solving a linear system

$$\nabla^2 f(x_k) d + \nabla f(x_k) = 0, \tag{18}$$

or to the solution of an equivalent system in the following form

$$\nabla F(x_k) \nabla F(x_k)^T d + B(x_k) d + \ldots + \nabla F(x_k) F(x_k) = 0. \tag{19}$$

At the optimal solution point x^*, the following condition is satisfied

$$F(x^*) = \left(f_1(x^*),..., f_l(x^*)\right)^T = 0, \tag{20}$$

therefore, finding the motion step d can be reduced to solving the normal equation of the least squares problem

$$\min_{d \in R^n} \left\| \nabla F(x_k)^T d + F(x_k) \right\|, \tag{21}$$

from which a recurrent equation $x_{k+1} = x_k + \alpha_k d_k$ can be obtained for iteratively finding the vector of desired parameters, in which is the solution d_k to the optimization problem, and α_k is an experimentally determined parameter.

This algorithm uses the Gauss–Newton method, which is a traditional algorithm for solving the non-linear least squares problem, to calculate the direction of motion. In the general case, the Gauss-Newton method makes it possible to obtain a solution to the problem of sequential quadratic programming using only first-order derivatives, but in real situations it often fails to obtain a solution.

Therefore, to improve convergence, second-order methods are used, in which the matrix of second derivatives of the objective function is used - the Jacobian matrix when solving optimization problems without restrictions. Second-order algorithms, compared to first-order methods, allow one to efficiently obtain a solution in a region close to the optimal point, when the components of the gradient vector have sufficiently small values.

Recently, methods using Levenberg-Marquardt algorithms have become widespread in quasi-Newtonian methods. The idea of these methods is to replace the Hesse matrix with some matrix $\lambda_k I$ with a positive coefficient λ_k. Then we obtain the following system of linear equations

$$\nabla F(x_k) \nabla F(x_k)^T d + \lambda_k d + \nabla F(x_k) F(x_k) = 0. \tag{22}$$

There are many different methods for solving the non-linear least squares problem without restrictions. On the other hand, there is a simple approach for combining the properties of the Gauss-Newton method with the method of sequential quadratic programming. The main problem of applying the method of sequential quadratic programming is the need to use special methods to ensure negative eigenvalues when approximating the Hess matrix in the case of alternative approaches.

Deterministic optimization methods such as linear programming and non-linear programming are widely used to solve multiobjective optimization problems.

However, these methods use a one-point approach and the result of these classical optimization methods is a single optimal solution. For example, the method of the weighted sum of local criteria transforms the multicriteria optimization problem into a single-criteria optimization problem, which makes it possible to obtain one point on the front of Pareto-optimal solutions.

To find the global optimum from Pareto optimal solutions, it is necessary to consider all possible Pareto fronts. In this case, it is necessary that the algorithms for finding the global optimum point are performed iteratively, so as to ensure that each combination of weights has been used.

To exhaust all combinations of weight, it is necessary to repeat the algorithms of such a local search many times. Therefore, algorithms must be able to «learn» from the solutions obtained in order to guide the correct choice of weight in further evolutions. When using classical methods for finding a global optimal solution, problems arise if the optimal solution is located in non-convex or disconnected regions of the functional space.

Recently, metaheuristic methods such as evolutionary algorithms and group intelligence technologies have become increasingly popular for solving the optimization problem [48-50]. Evolutionary methods, due to their efficiency and simplicity, have been successfully used to solve optimization problems with one objective function. These methods have some advantages over classical optimization methods, since they allow calculating optimal solutions for non-linear and non-convex functions [51-53].

They use the set of solutions in each iteration and stochastic search, and therefore they can find a search anywhere in the entire search space and are able to overcome the problems of local optima. Stochastic search methods are also more suitable for solving problems of multiobjective optimization.

Among the metaheuristic techniques, until recently, particle swarm optimization was applied only to single-objective optimization problems. The high convergence rate of particle swarm optimization algorithms for developing a multi-objective optimization algorithm has some advantages in terms of better exploration and exploitation provided by the algorithm's global search capability.

In the standard particle swarm optimization algorithm, particle velocities change according to linear laws, in which the movement of particle i swarm j is described by the following expressions [49]

$$\begin{aligned} v_{ij}(t+1) &= c_{1j} r_{1j}(t) \times \ldots \\ \ldots &\times \left[y_{ij}(t) - x_{ij}(t)\right] + c_{2j} r_{2j}(t) \times \ldots, \\ \ldots &\times \left[y_j^*(t) - x_{ij}(t)\right] \end{aligned} \tag{23}$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1), \tag{24}$$

where, are the position $x_{ij}(t)$ and speed $\upsilon_{ij}(t)$ of the particle i of the swarm j; c_1, c_2 – positive constants that determine the weights of the cognitive and social components of the speed of particle movement; $r_{1j}(t)$, $r_{2j}(t)$ 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 improving the quality of the optimization process.

In order to increase the speed of finding a global solution, special nonlinear algorithms of stochastic multi-agent optimization have recently become widespread [51-53].

Naturally, the formalization of the solution of the multiobjective optimization problem by reducing it to a single-objective problem makes it possible to reasonably choose one single point from the area of compromises – the Pareto area [48]. 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 [52, 53].

Simulation results. Let us consider the results of the design of combined electromagnetic passive and active shielding of overhead power lines magnetic field generated by a double-circuit power line in a residential building, as shown in Fig. 2.

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

Figure 3 shows the scheme of the shielding system design.

Figure 4 shows the distribution of the calculated initial magnetic field induction.

Figure 5 shows the distribution of the calculated resulting magnetic field induction whith only electromagnetic passive shield. The calculated shielding factor maximum value of resulting magnetic field whith only electromagnetic passive shield is more 4 units.

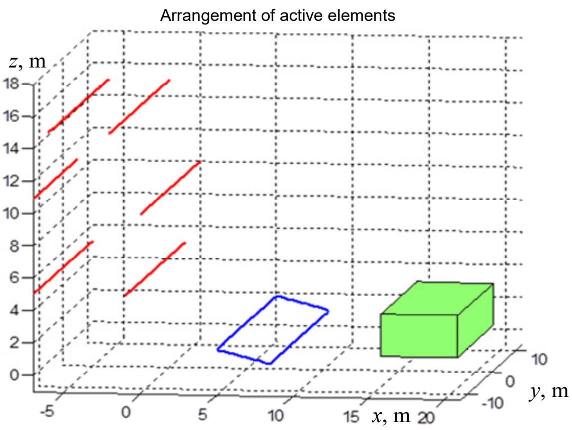

Fig. 3. Scheme of the shielding system design

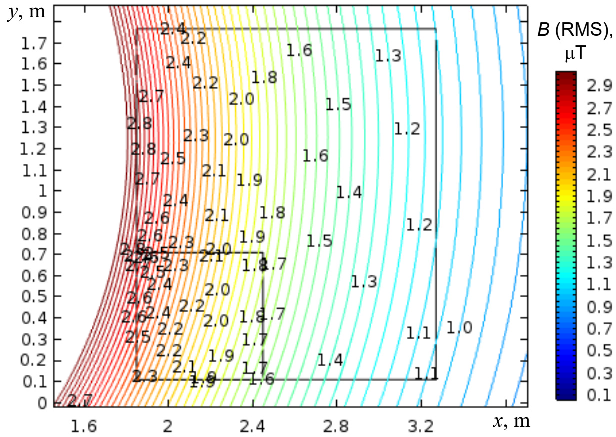

Fig. 4. Distribution of the calculated initial magnetic field induction

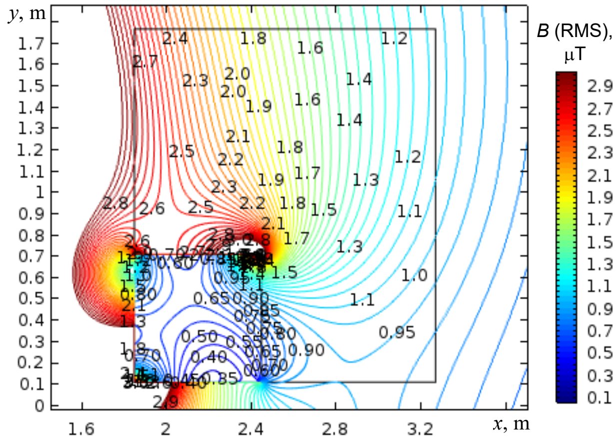

Fig. 5. Distribution of the calculated resulting magnetic field induction with only electromagnetic passive shield

Figure 6 shows the distribution of the calculated resulting magnetic field induction with only active shield. The calculated shielding factor maximum value of resulting magnetic field whith only active shield is more 4 units.

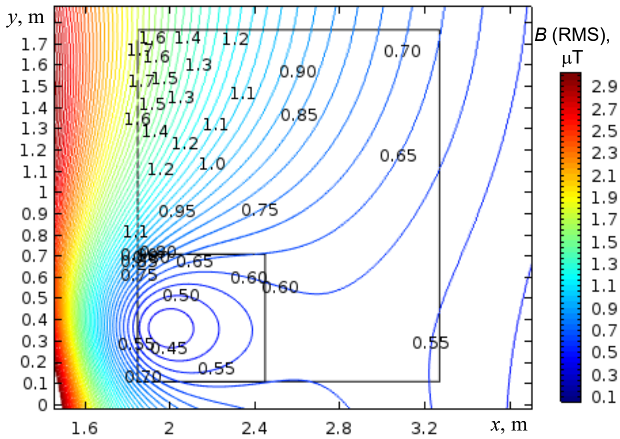

Fig. 6. Distribution of the calculated resulting magnetic field induction with only active shield

Figure 7 shows the distribution of the calculated resulting magnetic field induction with electromagnetic passive and active shield. The calculated shielding factor maximum value of resulting magnetic field whith electromagnetic passive and active shield is more 13 units.

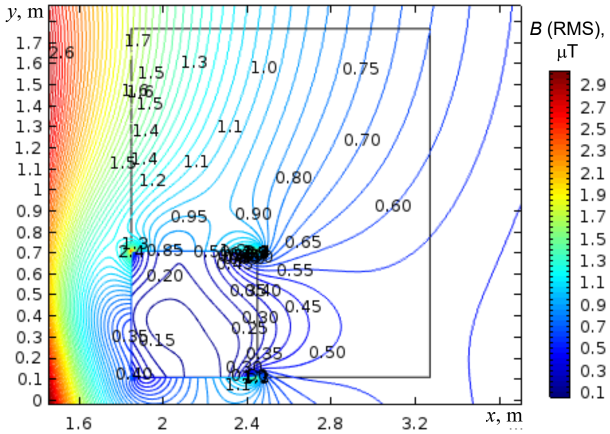

Fig. 7. Distribution of the calculated resulting magnetic field induction with combined electromagnetic passive and active shield

Results of experimental studies. Let us now consider the results of experimental studies of the electromagnetic passive and active shielding.

Figure 8 shows the compensation winding and electromagnetic passive shield of the experimental setup.

Figure 9 shows the control system of the experimental setup of electromagnetic passive and active shielding.

Fig. 8. Compensation winding and electromagnetic passive shield of the experimental setup of electromagnetic passive and active shielding

Fig. 9. Control system of the experimental setup

Figure 10 shows the experimental spatio-temporal characteristic of the initial magnetic field.

Figure 11 shows the experimental shielding factor of resulting magnetic field whith only electromagnetic passive shield. The experimental shielding factor maximum value of resulting magnetic field whith only electromagnetic passive shield is more 2 units.

Figure 12 shows the experimental spatio-temporal characteristic of the resulting magnetic field with only electromagnetic passive shield.

The experimental spatio-temporal characteristic of the resulting magnetic field with only electromagnetic passive shield is about 2 times less than the original characteristic, which is shown in Fig. 10 and rotated counterclockwise about 20 degrees clockwise.

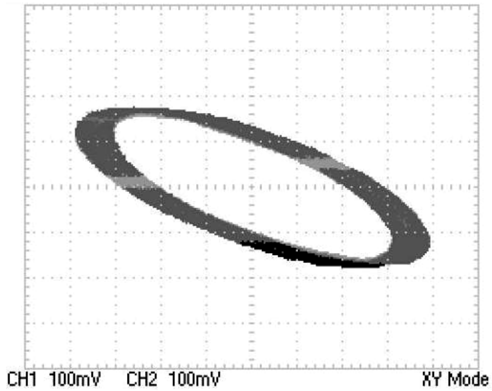

Fig. 10. Experimental spatio-temporal characteristic of the initial magnetic field

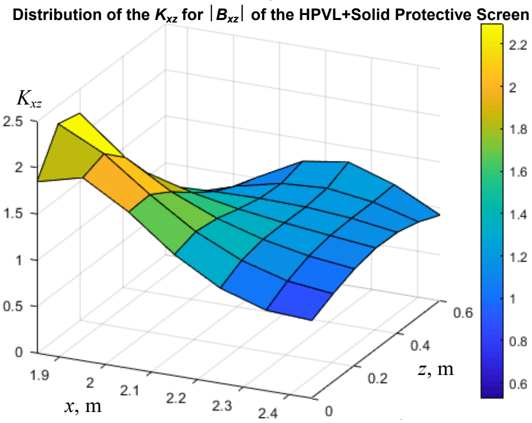

Fig. 11. Experimental shielding factor of resulting magnetic field with only electromagnetic passive shield

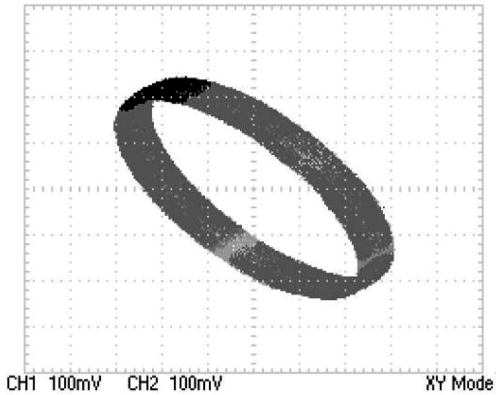

Fig 12. Experimental spatio-temporal characteristic of the resulting magnetic field with only electromagnetic passive shield

Figure 13 shows the experimental shielding factor of resulting magnetic field whith only active shield. The experimental shielding factor maximum value of resulting magnetic field whith only active shield is more 5 units.

Figure 14 shows the experimental spatio-temporal characteristic of the resulting magnetic field with only active shield. The experimental spatio-temporal characteristic of the resulting magnetic field with only active shield actually represents a point which is blurred by the noise of the magnetic sensors of the spatio-temporal characteristic measurement system.

Figure 15 shows the experimental shielding factor of resulting magnetic field with electromagnetic passive and active shield. The experimental shielding factor maximum value of resulting magnetic field with electromagnetic passive and active shield is more 10 units.

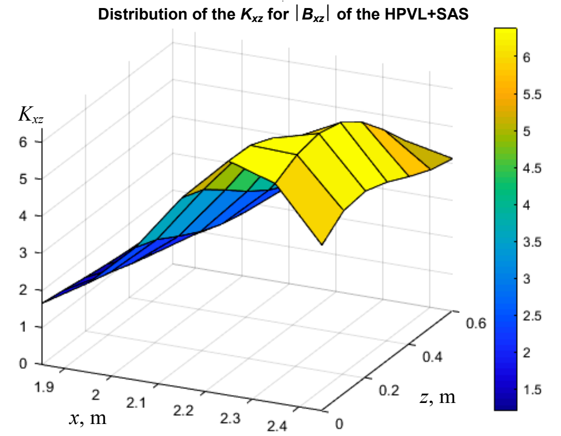

Fig. 13. Experimental shielding factor of resulting magnetic field whith only active shield

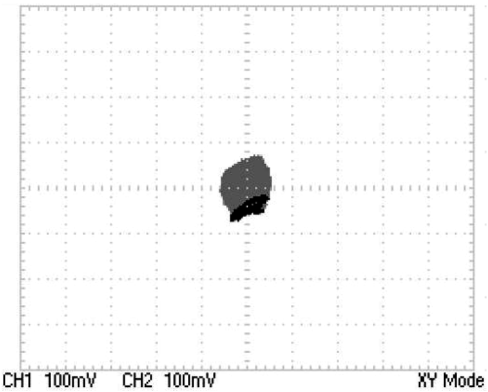

Fig. 14. Experimental spatio-temporal characteristic of the resulting magnetic field with only active shield

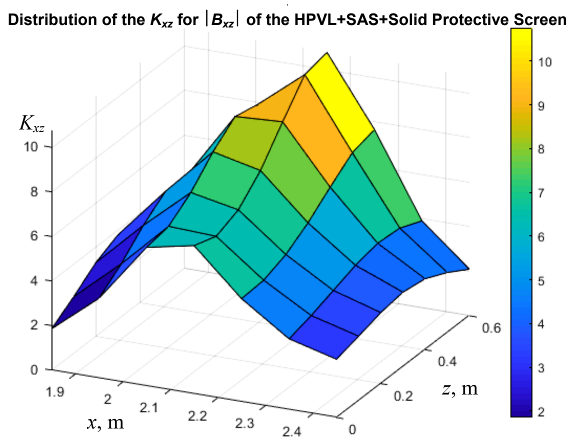

Fig. 15. Experimental shielding factor of resulting magnetic field with combined electromagnetic passive and active shield

Conclusions.

1. For the first time the method of designing a combined electromagnetic shield, consisting of active and passive parts, to improve the effectiveness of reduction of industrial frequency magnetic field created by two-circuit overhead power lines in residential buildings.

2. The problem of design of combined electromagnetic passive and active shielding solved based on the multi-criteria two-player antagonistic game. The game payoff vector calculated based on the finite element calculations system COMSOL Muliphysics. The solution of this game calculated based on algorithms of multi-swarm multi-agent optimization from sat of Pareto-optimal solutions based on binary preferences.

3. During the design of combined electromagnetic passive and active shields spatial location coordinates of shielding winding, the currents and phases in the shielding winding of active shielding, geometric dimensions and thickness of the electromagnetic passive shield are calculated.

4. Based on the developed method the combined electromagnetic passive and active shields for magnetic field generated by double-circuit overhead power lines in residential building were design. The results of calculating and experimental studi the shielding efficiency of the initial magnetic field using designed combined active and electromagnetic passive shielding are given.

5. The results of the performed theoretical and experimental studies have shown that the shielding factor is only passive electromagnetic screen made of a solid aluminum plate with a thickness of 1.5 mm is about 2 units, only active screen made in the form of a winding consisting of 20 turns is about 4 units. When using a combined electromagnetic passive and active screen, the shielding factor was more 10 units, which confirms its high efficiency, exceeding the product shielding factors of passive and active shields.

6. The practical use of the developed combined electromagnetic screen will allow reducing the level of the magnetic field in a residential building from a double-circuit power transmission line with a «barrel» type arrangement of wires to a safe level for the population 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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