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The method of multi-objective parametric design of magnetic field active canceling robust system for residential multy-story buildings closed to double-circuit overhead power lines

Aim. *Development the method of multi-objective parametric design for robust system of active canceling of magnetic field based on binary preference relations of local objective for multi-objective minimax optimization problem.* ***Methodology***. *Spatial location coordinates of the compensating winding and the current in the shielding winding were determined during the preference-based multi-objective parametric design of systems of active canceling based on solution of the vector minimax optimization, in whith the vector objective function calculated based on Biot-Savart's law. The solution of this vector minimax optimization problem calculated based on nonlinear Archimedes algorithm. Components of Jacobi matrix and Hesse matrix calculated based on multi-swarm multi-agent optimization.* ***Results.*** *Theoretically and experimentally confirmed the effectiveness of reducing the level of the magnetic field in residential multy-storey old building of a double-circuit overhead power transmission lines with a barrel-type arrangement of wires by means of active shielding with two compensation winding.* ***Originality.*** *The method of multi-objective parametric design for robust system of active canceling of magnetic field based on binary preference relations of local objective for multi-objective minimax optimization problem is developed.* ***Practical value***. *It is shown the possibility to reduce the level of magnetic field in residential multy-storey old building closed to double-circuit overhead power transmission lines with a barrel-type arrangement of wires by means of system of active canceling with two canceling winding to a level safe for the population with an induction of 0.5 μT.* References 52, figures 8.

Key words: **double-circuit overhead power transmission line, barrel-type arrangement of wires, magnetic field, system of active canceling, multi-objective parametric design, computer simulation, experimental research**.

Мета. *Розробка методу багатокритеріального параметричного проектування системи активного екранування на основі бінарних відносин переваги локальних критеріїв векторної мінімаксної оптимізації.* ***Методологія***. *Просторові координати розташування компенсаційних обмоток та струми в цих обмотках визначали під час багатокритеріального параметричного проектування системи активного екранування на основі бінарних відносин переваги векторної мінімаксної оптимізації, в якій векторна цільова функція розрахована на основі закона Біо-Савара. Рішення цієї задачи векторної мінімаксної оптимізації розраховано на основі нелінійного алгоритму Архімеда. Елементи матриць Якобі та Гессе розраховано на основі багаторойної багатоагентної оптимізації.* ***Результати***. *Теоретично та експериментально підтверджена ефективність зниження рівня магнітного поля в житлових багатоповерхових приміщеннях старої забудови дволанцюгових повітряних ліній електропередачі з бочкоподібним розташуванням проводів за допомогою активного екранування з двома компенсаційними обмотками.* ***Оригінальність***. *Розроблено метод багатокритеріального параметричного проектування системи активного екранування на основі бінарних відносин переваги локальних критеріїв векторної мінімаксної оптимізації.* ***Практична цінність***. *Показана можливість зниження рівня магнітного поля в житлових багатоповерхових приміщеннях старої забудови дволанцюгових повітряних ліній електропередачі з бочкоподібним розташуванням проводів за допомогою активного екранування з двома компенсаційними обмотками до до безпечного для населення рівня з індуцією 0,5 μТ.* Бібл. 52, рис. 8.

Ключові слова: **дволанцюгова повітряна лінія електропередачі, бочкоподібне розташування проводів, магнітне поле, система активного екранування, багатокритеріальне параметричне проектування, комп'ютерне моделювання, експериментальні дослідження.**

Introduction. According to the experts of the World Health Organization [1] and European Parliament [2], electromagnetic pollution of the environment at the end of the 20th century reached a level typical of pollution by harmful chemical substances. Therefore, the reduction of the techno genic electromagnetic field in the residential and natural environment has now become one of the primary global environmental problems that determine the quality and life expectancy of people, the preservation and reproduction of biotic and landscape diversity.

High-voltage power lines are one of the most dangerous sources of electromagnetic fields for people. They create in the surrounding space an intense magnetic field of power frequency, which covers large populated areas. Experts of the World Health Organization [1], European Parliament [2] and Global Cancer Statistics: GLOBOCAN [3] discovered the carcinogenic properties of the magnetic field of power lines with its weak but long-term effect on people, which poses a threat to the health of hundreds of thousands of people living near power lines.

Therefore, over the past 15 years, sanitary standards constantly strengthened around the world from the maximum permissible level of magnetic field (MF) induction of power frequency and intensive research is being conducted to develop methods for normalizing the magnetic field [4–23].

In Ukraine, near one-story residential old buildings a single-circuit power lines with a triangular arrangement of wires most often pass, and near multi-storey residential old buildings double-circuit power lines with an arrangement of barrel-type wires most often pass [4–7]. As an example, such a line is shown in Fig. 1.

Fig. 1. Multi-storey residential old building closed to double-circuit power lines with an arrangement of barrel-type wires

System of active canceling (SAC) is an automatic control system that includes a control object – plant, amplifiers, measuring devices and the automatic control device itself. The system of active canceling is designed to cancelate for the induction of the initial magnetic field, i.e. the system of active canceling is designed to maintain the level of induction of the resulting magnetic field at a zero level. Consequently, according to the International Federation Automatic Control (IFAC) terminology [24, 25], according to the algorithm of the functioning of the system of active canceling, it is a stabilization system, and the initial magnetic field is a disturbing influence.

According to the IFAC terminology [24, 25], the control algorithm is a system with two degrees of freedom [26–29]. To implement the open-loop control algorithm, the SAC uses magnetic field sensors located outside the canceling zone. With the help of these sensors, the induction of the initial magnetic field is actually cut off and the open-loop control algorithm for the disturbing effect is implemented in the SAC.

To form currents in canceling windings according to the closed-loop control algorithm, the SAC uses magnetic field sensors located at points in the canceling space. Moreover, during the design of the SAC, it is necessary to determine not only the structures and parameters of the regulator of such a system with two degrees of freedom, but also to determine the number, as well as the spatial arrangement and spatial orientation of these magnetic field sensors.

Unlike the design of classical automatic control system, when the actuators are given [30–33], the main task of the SAC design is also to determine the number, as well as the spatial location and spatial orientation of canceling windings, with the help of which a canceling magnetic field is generated. These windings are essentially magnetic actuators of the SAC. At the same time, during the design of the SAC, it is also necessary to determine the number of ampere-turns in the canceling windings, which, along with the geometric opening of these windings, will make it possible to determine the parameters of the SAC power amplifiers [17–23].

A feature of the design of the SAC, in contrast to the design of classical automatic control system, is the need to implement a given algorithm of operation in stabilizing the resulting magnetic field at a zero level of induction not at one point in the canceling space, but at a plurality of points in the canceling space. Therefore, even with one cancelate winding, the output of such a single-circuit system of active canceling is the magnetic field induction vector at the considered points of the canceling space. In general, this vector is infinite–dimensional, since the canceling space under consideration contains an infinite number of points.

Therefore, the problem of system design is a multi-criteria optimization problem.The parameters of the initial magnetic field model are known inaccurately and change in time, and, therefore, the designed system must be robust. Therefore, the problem of designing such a robust system is a multi-criteria minimax optimization problem. In addition when designing sush system it is presence of conflict situations. Minimization of the level of induction at one point in space leads to an increase the level of induction at another point in space due to undercanceling or overcanceling of the initial magnetic field.

The purpose of this work is development the method of multi-objective parametric design for robust system of active canceling of magnetic field based on binary preference relations of local objective for multi-objective minimax optimization problem.

Statement of the problem of multi-objective parametric design of system of active canceling. Consider the design of robust SAC of magnetic field. Let us first consider the mathematical model of the induction of the initial magnetic field. Note that the effectiveness of the compensation of the initial magnetic field is determined by the ratio of the effective values of the inductions of the initial and resulting magnetic field. However, the SAC as a classical automatic control system is a dynamic system and operates in real time [18]. Therefore, for the synthesis of the SAC, a mathematical model of the instantaneous value of the induction vector of the initial magnetic field is required.

Let's set the instantaneous values of the currents $I(t)$ in the wires of the power transmission line. Then, the instantaneous value of the elementary induction vector $\mathrm{d}B(P_i, t)$ of the initial MF at the considered point of the space point P_i at the time t calculated based on Biot–Savart law [4, 5]

$$\mathrm{d}B(P_i,t)=\frac{\mu_0 I(t)}{4\pi}\frac{\mathrm{dL}_i\times R_i}{\left|R_i\right|^3}, \qquad (1)$$

where R_i is the vector from the differential current element generic field in point P_i, $\mathrm{d}L_i$ is the elementary length vector of the current element, μ_0 is the vacuum magnetic permeability. Based on (1) one can calculate instantaneous value of the initial magnetic field induction vector $B_P(P_i, t)$ at time t at points P_i generated by all wires of all transmission lines.

Let us introduce the vector X of the desired parameters of the SAC, the components of which are number and geometrical parameters and coordinates of compensating windings, the number of ampere-turns and the phase shift of the open-loop control current of each compensating winding, gain coefficients of closed current regulators of each compensating winding, number and location coordinates and spatial orientation angles of magnetic field sensors.

Let us introduce the vector δ of the parameters of the uncertainty of the control object of the SAC, the components of which are the parameters of the uncertainty of the mathematical model of the initial magnetic field and canceling windings [34–38].

Then for the specified values of the vectors X of the desired parameters of the SAC and the vector δ of the parameters of the uncertainty of the control object of the SAC, the instantaneous value of the induction vector $B_W(X, \delta, P_i, t)$ magnetic field can be calculated, generated by all canceling windings at the considered point P_i in space at the time t by integrating the instantaneous value of the differential of the elementary induction vector of the magnetic field generated by the elementary sections of all compensating windings.

Then the vector $B_R(X, \delta, P_i, t)$ of the instantaneous value of the induction of the resulting magnetic field can be calculated as the sum of the vector $B_P(P_i, t)$ of the instantaneous value of the induction of the initial agnetic field generated by the transmission line and the vector

$B_W(X, \delta, P_i, t)$ of the instantaneous value of the magnetic field induction generated by the all compensation windings

$$B_R(X,\delta,P_i,t) = B_P(P_i,t) + B_W(X,\delta,P_i,t). \quad (2)$$

Based on the vector $B_R(X, \delta, P_i, t)$ of the instantaneous value of the induction of the resulting magnetic field, integrating over time over the interval of the period of change in the induction of the magnetic field, the effective value of the induction $B_R(X, \delta, P_i)$ of the resulting magnetic field at the considered point P_i in the screening space can be calculated. Then the design problem of system of active canceling can be formulated as the following minimax optimization problem

$$B_R(X^*,\delta^*) = \min_X \max_\delta \max_{P_i} B_R(X,\delta,P_I). \quad (3)$$

As a result of solving this minimax optimization problem, it is necessary to find the minimum over the vector X, the maximum over the vector δ from the maximum value of the induction vector over the entire set of considered points P_i in the screening space. Note that in this minimax optimization problem, the desired vectors X and δ are the vectors of real values, the points P_i of the screening space under consideration are integer variables.

Although this minimax problem is a scalar optimization problem, the difficulties in solving this problem are primarily due to the fact that among the optimized variables there are both integer and real variables. To simplify the solution of this original scalar optimization problem, we reduce it to the solution of the vector optimization problem

$$B_R(X^*,\delta^*) = \min_X \max_\delta B_R(X,\delta). \quad (4)$$

In this problem, a vector objective function is introduced

$$B_R(X,\delta) = \langle B_R(X,\delta,P_1) \rangle. \quad (5).$$

The components $B_R(X, \delta, P_i)$ of which are the effective values of the induction of the resulting magnetic field at all considered points of the screening space. Despite the fact that the original minimax scalar optimization problem of (3) is reduced to solving the minimax vector optimization problem (4), the solution of this vector optimization problem is simpler, since its variables are real numbers.

In this minimax optimization problem it is necessary to find the minimum of the vector objective function by the vector X, but the maximum of the same vector objective function by the vector δ.

The method for solving a minimax vector optimization problem based on binary preference relations. If only one vector objective function is given, then the solution of the problem is the set of unimprovable solutions – the Pareto set of optimal solutions [39, 40]. From the point of view of practical application, such a statement of the optimization problem is an ill-posed problem, since the solution in the form of a Pareto optimal set of unimprovable solutions is devoid of engineering sense [41–43].

A feature of solving the design problem of the system of active canceling is the presence of conflict situations. An attempt to minimize the level of disease in one space while indicating the level of disease in other points in space using a canceling windings system.

The simplest approach to solving a vector optimization problem is to reduce a vector optimization problem to a scalar optimization problem by folding the vector criterion into a scalar criterion using the accepted trade-off scheme.

To comply with sanitary standards, it is necessary that the level of induction at all points of the considered shielding space does not exceed the maximum allowable level specified by sanitary standards, which makes it possible to normalize individual criteria of the vector criterion [42, 43]. Therefore, we normalize the real values $B_R(X, \delta, P_i)$ of the induction of the resulting magnetic field at a point P_i relative to the maximum allowable level $B_{\max}$ of induction, specified in sanitary standards as follows

$$B_{RN}(X,\delta,P_i) = B(X,\delta,P_I)/B_{\max}.$$

In this case, the normalized particular criteria $B_{RN}(X, \delta, P_i)$ are in the range $0 \le B_{RN}(X, \delta, P_i) \le 1$. Approximation of the normalized value i a particular criterion for one 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 minimax multicriteria optimization problem, the simplest nonlinear trade-off scheme is used, in which the original multicriteria problem was reduced to two one-criterion problems

$$X^* = \arg\min_{\vec{X}} \sum_{i=1}^{J} \alpha_i \left[1 - B_{RN}(X,\delta,P_I)\right]^{-1};$$
$$\delta^* = \arg\max_{\delta} \sum_{i=1}^{J} \alpha_i \left[1 - B_{RN}(X,\delta,P_I)\right]^{-1}, \quad (6)$$

where α_i is the weighting coefficients characterizing the importance of particular criteria and determining the preference for certain criteria by the decision-maker. Naturally, such a formalization of the solution of the multicriteria optimization problem by reducing it to a single-criterion 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 trade-off scheme (6) actually corresponds to the method of penalty functions with an interior point, since when approaching i criterion $B_{RN}(X, \delta, P_i)$ to one, 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. However, at the beginning of optimization, it is necessary to make sure that all particular criteria are in the admissible regions, i.e., that the conditions $0 \le B_{RN}(X, \delta, P_i) \le 1$ for all normalized partial criteria. Otherwise, particular criteria for which these conditions are not met are translated into direct restrictions.

This non-linear trade-off scheme allows criteria to be selected according to the intensity of the situation. If any criterion is close to its limiting value, then its normalized value approaches unity. Then this nonlinear compromise scheme, in fact, using a scalar criterion, reduces the problem of minimizing the sum of criteria to minimizing this criterion alone, 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 nonlinear trade-off scheme acts similarly to a simple linear trade-off scheme. Thus, with the help of this nonlinear compromise scheme, 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 nonlinear trade-off scheme satisfies the Pareto optimality condition, i.e. using this scheme, it is possible to determine a point from the region of unimprovable solutions.

The considered nonlinear trade-off scheme corresponds to the method of penalty functions with an interior point. This assumes that the starting point is valid. When synthesizing dynamical systems, there is usually a situation where the starting point is invalid. Moreover, as a result of multicriteria synthesis, some local criteria may not be met at all.

However, in fact, such an approach replaces one problem of an infinite set of Pareto optimal solutions with another, as a rule, even more difficult problem of an infinite set of optimal solutions for an infinite set of trade-off schemes of pleasant folding of a vector criterion into a scalar one. At the same time, both the original vector optimization problem is ill-posed, and the problem of determining the compromise scheme is also all-posed.

To correctly determine one single solution from the set of Pareto nonimprovable optimal solutions, it is necessary to supplement the initial formulation of the vector optimization problem in the form of a vector objective function with some additional conditions.

When calculating the both solutions (6) constraints on the geometric dimensions and coordinates of the spatial arrangement of the compensating windings , constraints on currents in the windings X, as well as constraints on the vector δ of the uncertainty parameters of the models and magnetic field active cancelling system in the form of vector constraints

$$G_B(X,\delta) \leq G_{B_{\max}} . \quad (7)$$

Taking into account restrictions on the required variables and values of the components of the vector objective function usually leads to some narrowing of the initial set of Pareto optimal solutions, however, as a rule, the set is the solution to such a problem.

However, in order to narrow this set to one point, in addition to the original vector objective function and restrictions, additional conditions for preferring individual solutions from the set of non-improvable Pareto optimal solutions are required. One of the correct approaches to solving the problem of vector optimization is the use of binary preference relations, which allow choosing the most preferable one from two unimprovable solutions.

To select one single solution from the Pareto optimal solutions, use binary preference relations.

A feature of the considered problem of the design of the system of active canceling is the possibility of setting such binary preference relations.

Of the two solutions presented for comparison of their Pareto optimal solutions, the more preferable solution is the one for which the maximum value of induction, chosen from the set of all considered points in the screening space, has the smallest value. The use of such a binary preference relation makes it possible to correctly choose from the entire Pareto set of unimprovable solutions such a solution that provides the minimum value of the maximum value of the induction on the entire set of considered points in the screening space.

To narrow these sets, we use binary preference relations in the form

$$\max_{i=1,m} \max_{\delta} B_R\left(P_i, X_j^*, \delta_j^*\right) < \max_{i=1,m} \max_{\delta} B\left(P_i, \ldots X_k^*, \delta_k^*\right). \quad (8)$$

Based on these relationships and (8), the X_j^* and δ_j^* solutions are more preferable than the X_k^* and δ_k^* solutions.

Consistent application of binary preference relations in solving a vector optimization problem allows one to correctly choose from the entire set of non-Pareto-improvable optimal solutions one – the only solution that is the most preferable from the entire set from the point of view of binary preference relations.

The Archimedes optimization algorithm for solving a minimax vector optimization problem. The feature of the considered problem of minimax vector optimization problem (5) is that calculation of the values of vector objective function, even for one value of the desired parameters, requires significant computational resources. First, to calculate the instantaneous values of the induction vectors of the resulting magnetic field at the considered points of the shielding space, it is necessary to integrate the expressions of the Biot–Savart law over the lengths of all wires of the power transmission line and compensating windings. Then, to calculate the effective values of the induction vectors at the considered points of the screening space, it is necessary to integrate the calculated instantaneous values of the induction vectors of the resulting magnetic in time over the interval of the magnetic field oscillation period.

Another feature of the considered problem of minimax vector optimization problem (5) is the presence of several local minima, due to the formation of the induction of the resulting magnetic field with the help of several wires of power transmission lines – three, six, nine, twelve, etc.; and several wires of compensation windings – one, two, three, six, twelve, twenty-four, etc. Moreover, these local extrema have very steep surfaces, which causes zigzag motions of getting stuck when searching for an extremum using first-order methods. Therefore, to find a globally optimal solution from a set of local criteria, it is necessary to apply special algorithms. Therefore, in order to find the optimal solution to this problem, it is necessary to carefully choose an algorithm that allows minimizing the number of calculations of the vector objective function.

Currently, the most widely used are multi-agent stochastic optimization methods that use only the speed of particles. To find the solution of minimax vector optimization problem (5) from Pareto-optimal decisions [39, 40] taking into account the preference relations, we used special nonlinear algorithms of stochastic multi-agent optimization [44, 45]. To calculate the components $X_{ij}(t)$ optimal values of the vector X of the desired parameters using the following steps

$$
\begin{aligned}
&X_{ij}(t+1) = X_{ij}(t) + V_{ij}(t+1), \\
&V_{ij}(t+1) = W_{1j}V_{ij}(t) + C_{1j}R_{1j}(t) * \ldots \\
&\ldots * H(P_{1ij}(t) - E_{1ij}(t))\big[Y_{ij}(t) - \ldots \\
&\ldots - X_{ij}(t)\big] + C_{2j}R_{2j}(t)H(P_{1ij}(t) - \ldots \\
&\ldots - E_{2ij}(t))\big[Y_j^*(t) - X_{ij}(t)\big],
\end{aligned}
\qquad (9)
$$

where $X_{ij}(t)$ and $V_{ij}(t)$ are the position and velocity of i particle of j swarm; $Y_{ij}(t)$ and Y_j^* – the best–local and global positions of the i particle, found respectively by only one i particle and all the particles of j swarm; random numbers $R_{ij}(t)$, $E_{ij}(t)$ and constants C_{ij}, P_{ij}, W_j are tuning parameters; H is the Heaviside function.

To calculate the optimal values of the vector δ using the similarly steps.

In fact, these algorithms are a first-order random search algorithm, since only the particle velocity is used in the search – the first-order derivative of the scalar objective function or the gradient of the vector objective function. When finding derivatives in deterministic search methods, this algorithm is usually referred to as gradient descent and the matrix of first derivatives is called as Jacobian.

In random search, the motion of the particle is carried out in the direction of the maximum growth of the component of the objective function, found in the process of random search. In general, this direction serves as an estimate of the direction of the gradient in a random search. Naturally, such an increment of the objective function serves as an analogue of the first derivative – the rate of change of the objective function.

First-order methods have good convergence in the region far from the local optimum, when the first derivative has significant values. The main disadvantage of first-order search methods, which use only the first derivative – the speed of particles, is their low efficiency of the search and the possibility of getting stuck in the search near the local minimum, where the value of the rate of change of the objective function tends to zero. At the same time, in the region of the local optimum, the second derivative, the acceleration of the movement of particles, on the contrary, has a large value and its use allows, theoretically, in one step, to get to the point of the local optimum without the occurrence of zigzag jamming movements when using the first-order search [39, 40].

Note that with deterministic search methods, along with first-order algorithms, second-order algorithms are also widely used. These are the algorithms in particular, the algorithms of Newton, Newton–Gaus, Newton–Raphson.

The update rule $X(t+1)$ in the Newton–Raphson algorithm is as follows

$$
\begin{aligned}
&X(t+1) = X(t) - \left(\frac{\partial^2 B_R(X,\delta)}{\partial X^2}(t)\right)^{-1} \times \ldots \\
&\qquad \ldots \times \frac{\partial B_R(X,\delta)}{\partial X}(t); \\
&\delta(t+1) = \delta(t) + \left(\frac{\partial^2 B_R(X,\delta)}{\partial \delta^2}(t)\right)^{-1} \times \ldots \\
&\qquad \ldots \times \frac{\partial B_R(X,\delta)}{\partial \delta}(t),
\end{aligned}
\qquad (10)
$$

where the Hessians elements are denoted as

$$
\left(\frac{\partial^2 B_R(X,\delta)}{\partial X^2}(t)\right), \quad \left(\frac{\partial^2 B_R(X,\delta)}{\partial \delta^2}(t)\right)
$$

and the Jacobians are denoted as

$$
\frac{\partial B_R(X,\delta)}{\partial X}(t), \quad \frac{\partial B_R(X,\delta)}{\partial \delta}(t)
$$

of vector objective function $B(X, \delta)$, respectively, for the desired vectors X and δ.

The solution of equation (10) requires an explicit inversion of the Hesse matrix. This process can be computationally intensive.

To date, the most widely used algorithms are Levenberg–Maquard [40]. The idea of these methods is to replace the Hesse matrix with some matrix, which is iteratively calculated.

The Jacobian components are the first derivatives of the vector objective function – gradient vectors, the components of which are the velocity of the corresponding components of the vector objective function with respect to the corresponding variables. The Hessian components are the second derivatives of the vector objective function, the components of which are the accelerations of the corresponding components of the vector objective function with respect to the corresponding variables.

The Hessian components $A_{ij}(t)$ – accelerations of i particle of j swarm calculated similarly (9) using the following expressions

$$
\begin{aligned}
&A_{ij}(t+1) = W_{2j}A_{ij}(t) + C_{3j}R_{3j}(t) \times \ldots \\
&\ldots \times H(P_{3ij}(t) - E_{3ij}(t))\big[Z_{ij}(t) - \ldots \\
&\ldots - V_{ij}(t)\big] + C_{4j}R_{4j}(t)H(P_{4ij}(t) - \ldots \\
&\ldots - E_{4ij}(t))\big[Z_j^*(t) - V_{ij}(t)\big],
\end{aligned}
\qquad (11)
$$

where $A_{ij}(t)$ the accelerations of i particle of j swarm; $Z_{ij}(t)$ and Z_j^* are the best–local and global velocity of the i particle, found respectively by only one i particle and all the particles of j swarm. Similarly (9) random numbers $R_{ij}(t)$, $E_{ij}(t)$ and constants $C_{ij}(t)$, $P_{ij}(t)$, W_j are tuning parameters, H is the Heaviside function.

To calculate the optimal values of the vector δ using the similarly steps (11).

The advantage of second-order algorithms is the ability to determine not only the direction of movement, but also the size of the movement step to the optimum, so that with a quadratic approximation of the objective function, the optimum is found in one iteration. When solving real non-linear programming problems, the use of second-order methods can significantly reduce the number of iterations to find the optimum. In particular, this is how the sequential quadratic programming or successive quadratic programming method works.

The price for this is more complex calculations that must be performed first to calculate the matrix of second derivatives – the Hessian matrix, and then to determine the direction of movement and the size of the step towards the optimum. Therefore, despite the decrease in the number of iterations, the total time to find the optimum using second-order algorithms may differ slightly from first-order methods.

To take these constraints (7) into account when searching for solutions, we used special particle swarm optimization method for constrained optimization problems [44–49]. To take these binary preference relations (8) into account when searching for solutions, we used special evolutionary algorithms for multiobjective optimizations [50–52].

The use of the Archimedes algorithm for calculating minimax vector optimization problem (5) solutions with vector constraints (7) and binary preference relations (8) it possible to significantly reduce the calculating time [39, 40].

Multi-objective parametric design of system of active canceling. Based on the developed method the parametric design of two-loops systems of active canceling of the magnetic field generated by 110 kV two-circuits overhead power lines with a «Barrel» type arrangement of wires in mujty-storey old building has been performed. As result of parametric design, the coordinates of the location of two canceling windings was calculated, as well as the currents and phases in two canceling windings.

In Fig. 2 are shown two-circuit power transmission line with the arrangement of wires of the «Barrel» type, two canceling windings and mujty-storey old building.

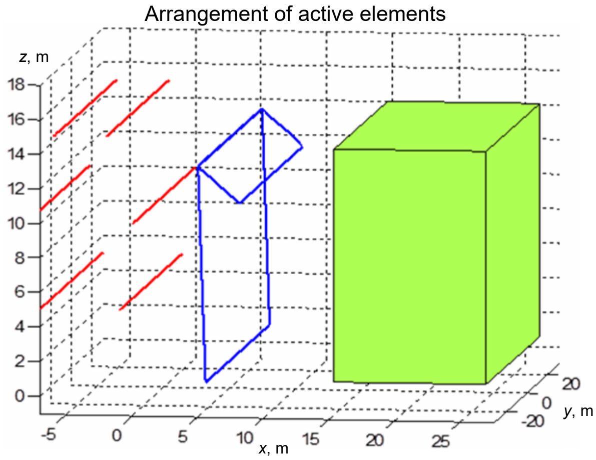


Fig. 2. Two-circuit power transmission line with the arrangement of wires of the «Barrel» type and two canceling windings

The system of active canceling contains two canceling windings. On Fig. 3 are shown the dependences of the calculated induction of the initial and resulting magnetic field.

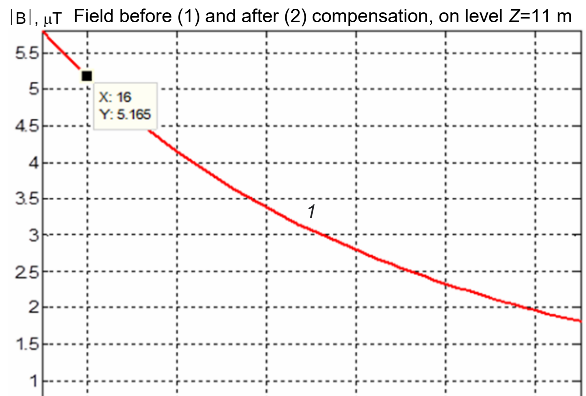


Fig. 3. Dependencies of the calculated induction of the initial and resulting magnetic field

The initial magnetic field induction is in the range from 5.75 μT to 1.8 μT. The resulting magnetic field induction does not exceed 0.2 μT in the entire range under consideration. The canceling factor more than 20 units.

The design of model of system of active canceling. To conduct experimental studies, a model of a two-circuit power transmission line with the arrangement of wires of the «Barrel» type in scale 7.5 was developed. On Fig. 4 is shown a photo of this model.

Fig. 4. Model of a two-circuit power transmission line with the arrangement of wires of the «Barrel» type

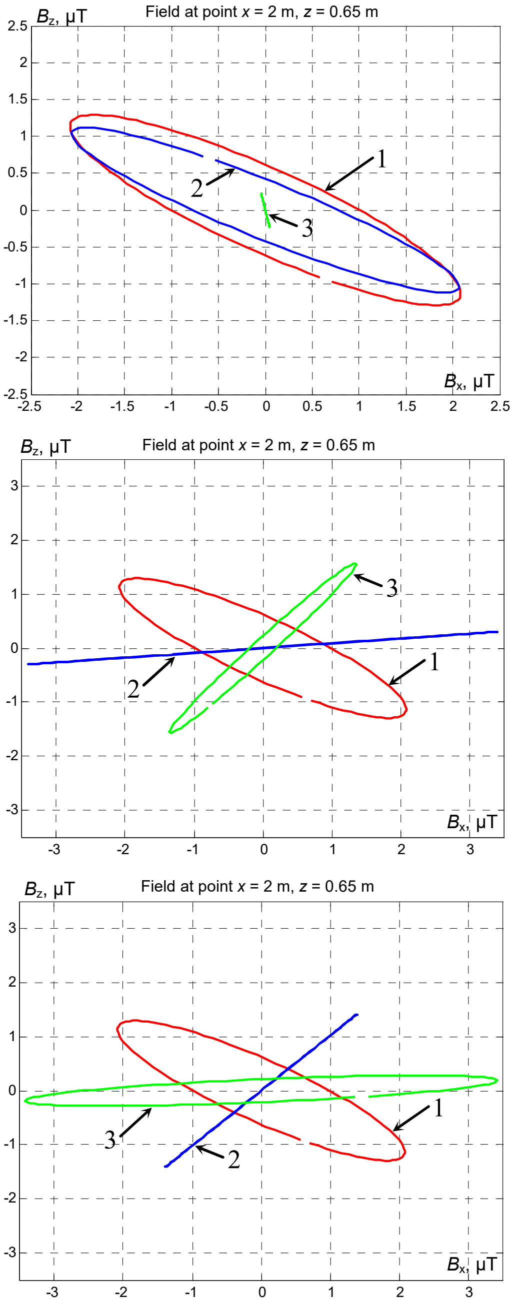
For this model, the system of active canceling was design. On Fig. 5 are shown a photo of the both canceling windings of the model of system of active canceling.

Fig. 5. Model of both canceling windings

Consider now spatiotemporal characteristic system of active canceling. In Fig. 6,*a* shows the spatiotemporal characteristic of the initial magnetic field, the resulting magnetic field and the spatiotemporal characteristic of the magnetic field generated only by both canceling windings.

As can be seen from Fig. 6,*a*, the spatiotemporal characteristic of the initial magnetic field and the magnetic field generated by two canceling windings practically coincide, and the spatiotemporal characteristic of the resulting magnetic field occupies a rather small area compared to the area of the spatiotemporal characteristic of the initial magnetic field, which causes a rather high value of the canceling factor – about ten units.

Let us now consider spatiotemporal characteristic of magnetic field when only single first canceling winding is in operation.



a

b

c

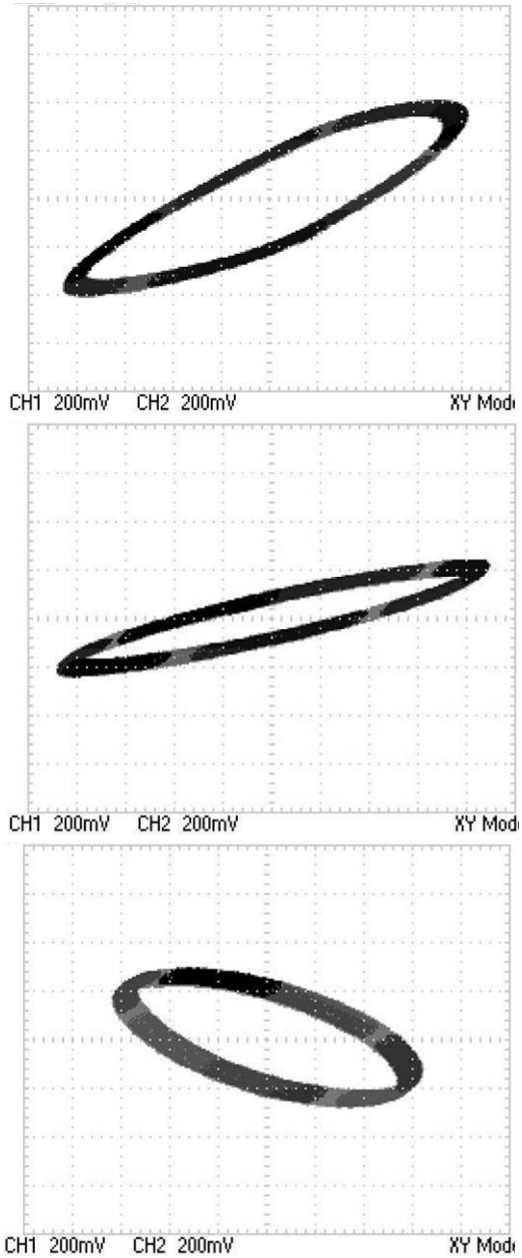
Fig. 6. The spatiotemporal characteristics of the initial magnetic field (1), the magnetic field generated only by compensation windings (2) and the resulting magnetic field (3)

Figures 6,*b* and Fig. 6,*c* show the spatiotemporal characteristic during the operation of only one first and only single second canceling windings. Note that when only one first or only one second canceling windings is working, there is a clear overcompensation of the initial magnetic field. At the same time, the efficiency of canceling of the initial magnetic field when only one first winding is operating is only 1.1 units, and when only one second winding is operating, the induction of the resulting magnetic field generally exceeds the induction of the original magnetic field by 1.5 times, so that the canceling factor ramen is less than unity and is 0.66 units.

The adjustment of model of system of active canceling. In the course of adjustment of model of system of active canceling it is necessary to experimentally determine the values of two phase shifts and two amplitudes of currents of open regulators and two gain factors of closed current regulators of both canceling windings.

First we consider spatiotemporal characteristic the resulting magnetic field generated by the power transmission line and only the first canceling winding. First, the magnitude of the phase shift and the amplitude of the current of the open-loop controller of the first winding were experimentally adjusting so that the spatiotemporal characteristic of the resulting magnetic field was parallel to the spatiotemporal characteristic generated only by the second winding, which is shown in Fig. 6,*c*. Such adjustment is necessary so that when the second winding is connected, it is possible to effectively compensate for the resulting magnetic field during the operation of the power transmission line and only the first winding.

On Fig. 7,*a* is shown the spatiotemporal characteristic of the resulting magnetic field during the operation of the power transmission line and only the first winding as a result of adjusting the open current regulators of the first winding.



a

b

c

Fig. 7. Experimentally measured spatiotemporal characteristic of the model of the system of active canceling

Then, for the attachment of an open current regulator of the second winding, we turn off the first winding. Now, the phase shift value and the amplitude of the current of the open-loop controller of the second winding are experimentally adjusted in such a way that the spatiotemporal characteristic of the resulting magnetic field is parallel to the spatiotemporal characteristic generated only by the first winding, which is shown in Fig. 7,*b*. Such adjustment is necessary so that when the first winding is connected, it is possible to effectively compensate for the resulting magnetic field during the operation of the power transmission line and only the second winding. On Fig. 7,*b* is shown the spatiotemporal characteristic of the resulting magnetic field during the operation of the power transmission line and only the second winding as a result of adjusting the open current regulators of the second winding.

Now, with the power transmission line turned on, we simultaneously turn on both windings and additionally adjust the open current regulators of the first and second windings so that the spatiotemporal characteristic of the resulting magnetic field has a minimum area. On Fig. 7,*c* is shown spatiotemporal characteristic of magnetic field generated by simultaneously operating the first and second windings. This spatiotemporal characteristic practically coincides with the spatiotemporal characteristic of the initial magnetic field generated only by the model of power transmission line and is shown in Fig. 7,*c*.

Results of experimental studies. Consider the effectiveness of canceling of initial magnetic field by model of the system of active canceling with the parameters of the controllers tuned when the model was adjustment. In Fig. 8 are shown experimentally measured *a*) induction of the initial and resulting magnetic field and *b*) canceling factor, which experimentally measured on the model of SAC.

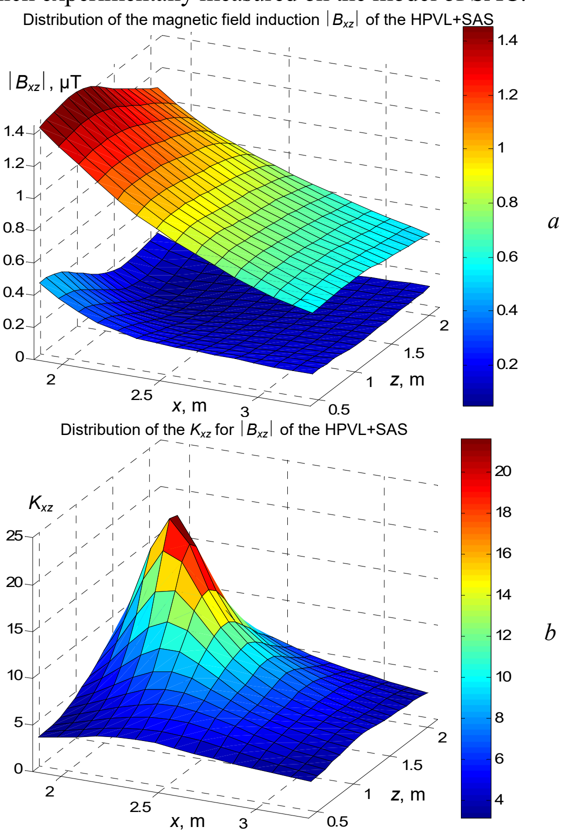


Fig. 8. Experimentally measured *a*) induction of the initial and resulting magnetic field and *b*) canceling factor of the model of SAC

As can be seen from this Fig. 8,*b*, the experimentally measured on the model of SAC canceling factor in a small area of space is 25 units.

Conclusions.

1. The method of multi-objective parametric design for robust system of active canceling of magnetic field based on binary preference relations of local objective for multi-objective minimax optimization problem was development.

2. The parametric design of robust system of active canceling according to the developed method reduced to computing the solution of vector minimax optimization problem based on binary preference relations. This solution calculated based on stochastic nonlinear Archimedes algorithms. Components of Jacobi matrix and Hesse matrix calculated based on multi-swarm multi-agent optimization. The vector of objective function of minimax optimization problem and constraints calculation based on Bio–Savart's law.

3. Using the developed method the parametric design of two-loops systems of active canceling of the magnetic field generated by 110 kV two-circuits overhead power lines with a «Barrel» type arrangement of wires in mujty-storey old building has been performed. As result of parametric design, the coordinates of the location of two canceling windings was calculated, as well as the currents and phases in two canceling windings.

4. Based on theoretical and experimental research on physical scale model of a double-circuit power transmission line it is shown the possibility to reduce the level of magnetic field in multy-storey old building from power transmission line with a «Barrel» type arrangement of wires by means of active canceling with two canceling winding with initial induction of 5.7 μT to a safe level for the population 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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