UDC 621.3.013 https://doi.org/10.20998/2074-272X.2023.4.04

B.I. Kuznetsov, T.B. Nikitina, I.V. Bovdui, O.V. Voloshko, V.V. Kolomiets, B.B. Kobylianskyi

Optimization of spatial arrangement of magnetic field sensors of closed loop system of overhead power lines magnetic field active silencing

Aim. *Development of a method for optimization of spatial arrangement and angular position of magnetic field sensors of a closed system to ensure maximum efficiency of active silencing canceling of the magnetic field generated by overhead power lines.* ***Methodology****. Spatial arrangement and angular position of magnetic field sensors of closed loop system of overhead power lines magnetic field active silencing determined based on binary preference relations of local objective for multi-objective minimax optimization problem, in whith the vector objective function calculated based on Biot–Savart law. The solution of this vector minimax optimization problem calculated based on nonlinear Archimedes algorithm of multi-swarm multi-agent optimization.* ***Results.*** *Results of simulation and experimental research of optimal spatial arrangement and angular position of magnetic field sensors of a closed system to ensure maximum efficiency of active silencing of the magnetic field generated by overhead power lines with a barrel-type arrangement of wires.* ***Originality.*** *The method for optimization of spatial arrangement and angular position of magnetic field sensors of a closed system to ensure maximum efficiency of active shielding of the magnetic field generated by overhead power lines is developed.* ***Practical value****. An important practical problem optimization of spatial arrangement and angular position of magnetic field sensors of a closed system to ensure maximum efficiency of active silencing of the magnetic field generated by overhead power lines has been solved.* References 53, figures 10.

Key words: **overhead power transmission line, magnetic field, system of active silencing, spatial arrangement and angular position of magnetic field sensors, multi-objective parametric optimization, computer simulation, experimental research**.

Мета. *Розробка методу оптимізації просторового розташування та кутового положення датчиків магнітного поля замкнутої системи для забезпечення максимальної ефективності активного екранування магнітного поля, яке створювається повітряними лініями електропередачі.* ***Методологія.*** *Просторове розташування та кутове положення датчиків магнітного поля для замкнутої системи активного подавлення магнітного поля, яке створюваєтьс повітряними лініями електропередачі, визначене на основі бінарних відношень переваги локальної цілі для багатокритерійної задачі мінімаксної оптимізації, в якій векторна цільова функція розрахована на основі закону Біо-Савара. Рішення цієї задачі векторної мінімаксимальної оптимізації обчислюється на основі нелінійного алгоритму Архімеда мульти-ройної багатоагентної оптимізації.* ***Результати.*** *Результати моделювання та експериментальних досліджень оптимального просторового розташування та кутового положення датчиків магнітного поля замкнутої системи для забезпечення максимальної ефективності активного екранування магнітного поля, яке створюється повітряними лініями електропередачі з бочкоподібним розташуванням проводів.* ***Оригінальність****. Розроблено метод оптимізації просторового розташування та кутового положення датчиків магнітного поля замкнутої системи для забезпечення максимальної ефективності активного екранування магнітного поля, яке створюється повітряними лініями електропередачі.* ***Практична цінність****. Вирішено важливу практичну задачу проектування оптимального просторового розташування та кутового положення датчиків магнітного поля замкнутої системи для забезпечення максимальної ефективності активного екранування магнітного поля, яке створюється повітряними лініями електропередачі.* Бібл. 53, рис. 10.

Ключові слова: **повітряна лінія електропередачі, магнітне поле, система активного екранування, просторове розташування та кутове положення датчиків магнітного поля, багатокритерійна параметрична оптимізація, комп'ютерне моделювання, експериментальні дослідження.**

Introduction. Electricity has given humanity many benefits. However, as is often the case, the same electricity has created certain problems for humanity. One of such problem is the power frequency magnetic field generated by overhead power lines (MF). Many of overhead power lines often pass in the residential areas and generated a magnetic field, the level of which often exceeds the safe level for the population with an induction of 0.5 μT adopted in Europe, that poses a threat to public health [1-3]. World Health Organization carries out the ongoing global programs connected with climate change, ionizing radiation, chemical safety, etc. The small number of these programs emphasizes the importance of the issues involved. The effect of the electromagnetic field on the population is one of such issues, and it is studied within the framework «The International EMF Project». Research results confirm the high risk of power frequency (50-60 Hz) MF for human health. This leads to modern world trends on stricter sanitary standards on reference levels of power frequency magnetic field.

Currently, strict sanitary standards for the magnetic field induction 0.5 μT have been introduced into the regulatory documents of the Ministry of Energy of Ukraine. However, in Ukraine these norms are universally exceeded, which poses a threat to the health of millions of people living closer than 100 ms from overhead power lines.

Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine carried out experimental research of magnetic field generate by high-voltage transmission lines 10-330 kV [4-7]. It is shown, that their magnetic field are 3-5 times higher than the standard level at the border of sanitary zones previously formed in the electric field. This situation requires urgent measures to reduce by 3-5 times the magnetic field of the existing power lines within the cities of Ukraine.

A similar situation is typical for most industrialized countries of the world [8-11]; however, in these countries, normalization technologies of magnetic field of existing power transmission lines have already been created and are widely used [12-16]. The most effective technology is the reconstruction of power transmission lines by removing it to a safe distance from residential buildings, or replacing an overhead transmission line with a cable line. However, such a reconstruction requires huge material resources. Therefore, less expensive methods of canceling the magnetic field of existing power transmission lines are more acceptable for Ukraine, of which the methods of active contour silencing of the magnetic field provide the necessary efficiency.

The technology of active contour silencing of magnetic field of existing power transmission lines has been developed and used in developed countries of the world for more than 10 years, for example, in the USA and Israel [17-23]. In Ukraine, at present, both such technology and the scientific foundations of its creation are absent.

The method is implemented using a system of active silencing. System of active silencing consists of silencing coils, with the help of which a silencing magnetic field is formed. The currents in canceling windings automatically generated by a certain algorithm as a function of the signal from the magnetic field sensors installed in the protection zone. For the power supply, the system of active silencing contains a current source that receives energy from an external source.

In the system of active silencing, a different number of canceling windings used, determined by the spatio-temporal characteristic of the initial magnetic field, the geometric dimensions of the silencing space and the required level of the resulting magnetic field in the silencing space. The most common transmission lines in Ukraine, passing near residential and public areas, are double-circuit power lines with a suspension of wires of the «barrel» type. Such transmission lines generate magnetic field, the spatiotemporal characteristic of which is a highly elongated ellipse.

For active silencing of such magnetic field, a single-circuit system of active silencing with one silencing winding is often sufficient. With the help of such system of active silencing, the major axis of the spatiotemporal characteristic ellipse compensated, which makes it possible to obtain a sufficient silencing efficiency of the initial magnetic field. In the area of old residential buildings, single-circuit power lines with a triangular suspension of wires often pass. Such transmission lines generate magnetic field, the spatiotemporal characteristic of which is a circle.

For active silencing of such a magnetic field, it is necessary to use at least a double-circuit system of active silencing with two canceling windings. If it is necessary to shield the magnetic field generated by such a power line in a multi-storey building, three or more silencing windings may be required, depending on the required level of the resulting magnetic field in the silencing space.

For the formation of currents in the silencing windings, open, closed and combined control algorithms can be used [24-29]. With an open-loop control algorithm for silencing windings, one canceling sensor is sufficient, with the help of which the induction of the initial magnetic field is measured [30-35]. This sensor installed outside the silencing space so that the silencing windings do not affect its operation [36-40].

The disadvantage of the open-loop control algorithm for the silencing windings is its relatively low efficiency of silencing the initial magnetic field [41-47]. In particular, with an open-loop control algorithm, it is impossible silencing for changes in the magnetic field induction inside the silencing spase, due to the presence of internal sources of magnetic field, as well as in the process of inevitable changes in the parameters of the system of active silencing control object during its operation [39, 40].

For the correct implementation of a closed algorithm for controlling by all silencing windings, the number of magnetic field sensors is usually equal to the number of silencing windings [30, 31]. Moreover, all these sensors installed inside the shielding space for the correct measurement of the resulting magnetic field generated both by power lines and by all silencing windings.

As an example, Fig. 1 shows a photo of the spatial arrangement of the sensor inside the silencing space, given in [16].

Fig. 1. Spatial arrangement of the magnetic field sensor inside the silencing space

Naturally, the efficiency of active silencing of the initial magnetic field with the help of each silencing windings and all simultaneously operating silencing windings depends on the spatial arrangement and orientation in the silencing space of all magnetic field sensors.

The aim of the work is to develop a method for optimization of spatial arrangement and angular position of magnetic field sensors of a closed system to ensure maximum efficiency of silencing of the magnetic field generated by overhead power lines.

Statement of the problem. Let us consider the formulation of the problem of correctly determining the coordinates of the spatial location and their angular orientation in the silencing space of all magnetic field sensors, which are necessary for the implementation of a closed control algorithm for all silencing windings. Let us introduce the vector Y of the desired parameters of the coordinates of the spatial arrangement and the vector φ of the desired parameters of the angular position of all magnetic field sensors at points Q_i in the silencing space. The components of the angular orientation vector of all magnetic field sensors are vectors of unit length, directed parallel to the desired angular positions of the axes of the magnetic field sensors.

Let us consider the mathematical model of the magnetic field generated in the silencing space by all the wires of the power transmission line and by all the magnetic field windings at the installation points Q_i of the canceling sensors in the magnetic field space. We set the vector $I_p(t)$ of instantaneous values of currents in all wires of the power transmission line of the three-phase current in the form of sinusoidal dependencies

$$I_i(t) = A\sin(\omega(t) + \varphi_i) \tag{1}$$

of the given frequency ω and the given phase φ_i, where i = 1, 2, 3 – the number of the conductor of the three-phase current line.

Then, the instantaneous value of the elementary induction vector $\mathrm{d}B(Q_i, t)$ of the initial magnetic field at the considered point of the space point Q_i at the time t calculated based on Biot–Savart law [4, 5]

$$\mathrm{d}B(Q_i, t) = \frac{\mu_0 I(t)}{4\pi} \frac{\mathrm{d}L_i \times R_i}{|R_i|^3}, \tag{2}$$

where R_i is the vector from the differential current element generic field in point Q_i, $\mathrm{d}L_i$ is the elementary length vector of the current element, μ_0 is the vacuum magnetic permeability. The sign × denotes the vector product of the vectors dL_i and R_i.

Based on (2) for vector $I_p(t)$ of instantaneous values of currents in all wires of the power transmission line (1) by integrating over the entire length of all current wires of power transmission lines calculated instantaneous value of the initial magnetic field induction vector $B_p(Q_i, t)$ at time t at points Q_i generated by all wires of all transmission lines.

Let us first assume that the number and geometric dimensions of canceling windings are given. Let us set the column vector $I_W(t)$ of the instantaneous values of the currents in the canceling windings. Then, for the given values of the geometric dimensions of the canceling windings and the vector $I_W(t)$ of the instantaneous values of the currents of the instantaneous values of the currents in the silencing windings, based on the Biot–Savart law, similarly (1) calculated the instantaneous value of the magnetic field induction vector $B_W(Q_i, t)$ generated by all wires of all silencing windings at time t at points Q_i.

Then the vector $B_R(Q_i, t)$ of the instantaneous values of the induction of the resulting magnetic field generated by all wires of the power transmission line and all silencing windings at time t at points Q_i in silencing space

$$B_R(Q_i,t) = B_P(Q_i,t) + B_W(Q_i,t) \tag{3}$$

Based on this vector $B_R(Q_i, t)$ of the instantaneous values of the induction of the resulting magnetic field vectors at the installation points Q_i of the magnetic field sensors, taking into account the vector φ of the spatial position angles of the magnetic field sensors, the vector $B_M(Q_i, t)$ of the projections of the vector $B_R(Q_i, t)$ of the instantaneous values of the induction of the resulting magnetic field onto the vector φ of the angular positions of these magnetic field sensors calculated

$$B_M(Q_i,t) = B_R(Q_i) \otimes \varphi, \tag{4}$$

here the sign ⊗ denotes the tensor (Kronecker) product of the column vectors. In this case, the elements of the vector $B_M(Q_i, t)$ are the result of the element-by-element scalar multiplication of the components of the column vector $B_R(Q_i, t)$ and the column vector φ. The components of the projection vector $B_M(Q_i, t)$ are scalar values obtained as a result of component-by-component scalar multiplication of the resulting magnetic field induction vectors $B_R(Q_i, t)$ at the magnetic field sensor installation point by unit vectors φ of the angular position of the magnetic field sensors.

The components of this vector $B_M(Q_i, t)$ of projections of the $B_R(Q_i, t)$ vector of instantaneous values of the induction of the resulting magnetic field are the instantaneous values of the voltages $I_W(t)$ at the outputs of the magnetic field sensors

$$y_M(t) = B_R(Q_i,t) \otimes \varphi \otimes K_M + w(t), \tag{5}$$

where $w(t)$ is the magnetometer noise vector.

This takes into account the vector column K_M of the gain coefficients of the magnetic field sensor taking into account the number of turns of their measuring coils and the gains of the preamplifiers.

Let's take the structure of the system of active shielding of the magnetic field in the following form: we will apply the output voltage $y(t)$ of the corresponding magnetometer to the input $u(t)$ of the PID controller of each channel. Let's write the differential state equation of discrete PID regulators, the input of which is the vector $y(t)$ of measured magnetic field induction components, and the output is the vector $u(t)$ of plant control

$$x_c(t+1) = A_c x_c(t) + B_c y(t), \tag{6}$$

$$u(t) = C_c x_c(t) + D_c y(t), \tag{7}$$

in which the elements of the matrices A_c, B_c, C_c, D_c are determined by the PID parameters of the regulators.

Let's write down the models of the control objects of each channel, the input of which is the vector $u(t)$ of output voltages of the PID controller, and the output of which is the vector $I_W(t)$ of instantaneous values of currents silencing windings

$$x_p(t+1) = A_p x_p(t) + B_p u(t), \tag{8}$$

$$I_w(t) = C_p x_p(t) + D_p u(t), \tag{9}$$

in which the elements of the matrices A_p, B_p, C_p, D_p are determined by the parameters of the model of the control object, which includes a silencing windings, a power amplifier and current regulator.

Thus, with the help of (4) – (9), the instantaneous value of the current vector $I_W(t)$ in the silencing windings formed in the form of feedback on the vector $B_R(Q_i, t)$ of the induction of resulting magnetic field (3).

Let us introduce the vector X of desired parameters, the components of which are the vector Y of the desired parameters of the coordinates of the spatial arrangement, the vector φ of the desired parameters of the angular position of all magnetic field sensors at points Q_i in the screening space and the desired column vector K of the gain coefficients of the silencing windings PID controllers. Note that if the parameters of the geometric dimensions of the silencing windings not specified, then they can be included in the vector vector X of desired parameters. Let us introduce olso the vector δ of the parameters of the uncertainty of the control object of the system of active silencing, the components of which are the parameters of the uncertainty of the mathematical model of the initial magnetic field and silencing windings [34-38].

We introduce M points P_i in the screening space. Note that the considered M points P_i of the silencing space are selected for reasons of providing a given level of induction of the resulting magnetic field in the entire given silencing space, and their number and spatial arrangement may not correspond to the installation points of the magnetic field sensors. These points usually chosen over the entire silencing space, since with the help of the system of active canceling it is possible to overcompensate the magnetic field near the power line and undercompensate the initial magnetic field away from the power line.

Then based on (2) for vector $I_p(t)$ of instantaneous values of currents in all wires of the power transmission line (1) by integrating over the entire length of all current wires of power transmission lines calculated instantaneous value of the initial magnetic field induction vector $B_p(Q_i, t)$ at time t at points P_i generated by all wires of all transmission lines.

Then, for the given values of the geometric dimensions of the silencing windings and the vector $I_W(t)$ of the instantaneous values of the currents of the instantaneous values of the currents in the silencing windings calculated by (5), based on the Biot–Savart law, similarly (1) calculated the instantaneous value of the magnetic field induction vector $B_W(X, \delta, P_i, t)$ generated by all wires of all silencing windings at time t at points P_i.

Then the vector $B_R(X, \delta, P_i, t)$ of the instantaneous values of the induction of the resulting magnetic field generated by all wires of the power transmission line and all silencing windings at time t at points P_i in silencing space

$$B_R(X,\delta,P_i,t) = B_P(P_i,t) + B_W(X,\delta,P_i,t)\,. \tag{10}$$

Let us introduce an M dimensional vector $B_R(X, \delta, P_i)$ of effective values of the resulting magnetic field at M points in the silencing space, calculated by integrating the square of the modulus of the instantaneous value vector $B_R(X, \delta, P_i, t)$ over the interval of the network voltage change period.

Then the design problem of vector X parameters of the coordinates of the spatial arrangement, the vector φ of the desired parameters of the angular position of all magnetic field sensors at points Q_i in the silencing space and the desired column vector K of the gain coefficients of the silencing windings controllers reduces to solving vector minimax optimization wits vector objective function

$$B_R(X,\delta) = \langle B_R(X,\delta,P_1)\rangle\,. \qquad (11).$$

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 Q_i in the silencing space.

In this minimax optimization problem it is necessary to find the minimum of the vector objective function (11) by the vector X, but the maximum of the same vector objective function by the vector δ.

At the same time, naturally, it is necessary to take into account restrictions on the control vector and state variables in the form of vector inequality and, possibly, equality

$$G(X) \le G_{\max}, \quad H(X) = 0\,. \tag{12}$$

Note that the components of the vector criterion (11) and constraints (12) are the nonlinear functions of the vector of the required parameters of the regulators and their calculation is performed basis on the Biot–Savart law [5, 6].

The method for problem solving. The solution of the vector minimax optimization problem wits vector objective function (11) is the set of unimprovable solutions – the Pareto set of optimal solutions if only one vector objective function is given [48, 49]. 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 from the point of view of practical application [50, 51]. In addition to the vector optimization criterion (11) and constraints (12), it is also necessary to have information about the binary relations of preference of local solutions to each other in order to correctly solve the problem of multi-criteria optimization. This approach makes it possible to significantly narrow the range of possible optimal solutions to the original multi-criteria optimization problem.

The problem of finding a local minimum at one point of the considered space is, as a rule, multi-extreme, containing local minima and maxima, therefore, for its solution, it is advisable to use algorithms of stochastic. 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 (11) from Pareto-optimal decisions [48, 49] taking into account the preference relations, we used special nonlinear algorithms of stochastic multi-agent optimization [50, 51]. 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. 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 found in one iteration.

To search the components $X_{ij}(t)$ optimal values of the vector X of the desired parameters minimizing vector optimization criterion (11) under constraints (12), for calculating velocities $V_{ij}(t)$ and accelerations $A_{ij}(t)$ of i particle of j swarm using the following steps

$$\begin{aligned} &V_{ij}(t+1) = W_{1j}V_{ij}(t) + C_{1j}R_{1j}(t)\times \\ &\times H(P_{1ij}(t) - E_{1ij}(t))\big[Y_{ij}(t) - \\ &- X_{ij}(t)\big] + C_{2j}R_{2j}(t)H(P_{1ij}(t) - \\ &- E_{2ij}(t))\big[Y_j^*(t) - X_{ij}(t)\big]; \end{aligned} \tag{13}$$

$$\begin{aligned} &A_{ij}(t+1) = W_{2j}A_{ij}(t) + C_{3j}R_{3j}(t)\times \\ &\times H(P_{3ij}(t) - E_{3ij}(t))\big[Z_{ij}(t) - \\ &- V_{ij}(t)\big] + C_{4j}R_{4j}(t)H(P_{4ij}(t) - \\ &\ldots - E_{4ij}(t))\big[Z_j^*(t) - V_{ij}(t)\big], \end{aligned} \tag{14}$$

here $Y_{ij}(t)$ and Y_i^* – the best-local and global positions $X_{ij}(t)$, $Z_{ij}(t)$ and Z_i^* – the best-local and global velocity $V_{ij}(t)$ of the i-th particle, found respectively by only one i-th particle and all the particles of j swarm.

Random numbers $R_{ij}(t)$, $E_{ij}(t)$ and constants C_{ij}, P_{ij}, W_i are tuning parameters, H is the Heaviside function.

To search the components $X_{ij}(t)$ optimal values of the vector δ of the parameters of the uncertainty of the control object (2) of the system of active silencing maximizing the same vector optimization criterion (11) under constraints (12), for calculating velocities $V_{ij}(t)$ and accelerations $A_{ij}(t)$ of i particle of j swarm using the steps similarly (13) – (14). However, unlike (13) and (14), the best local and global position and velocity components are those that lead not to a decrease in the corresponding components of the vector objective function (11), but vice versa to their increase. This is where the «malicious» behavior of the vector δ of uncertainties of the designed system is manifested.

The use of the Archimedes algorithm [53] for calculating minimax vector optimization problem (11) solutions with vector constraints (12) and binary preference relations it possible to significantly reduce the calculating time [51, 52].

Results of design of experimental model. As an example, consider the design of optimal spatial arrangement and angular position of magnetic field sensors for a closed system to ensure maximum efficiency of active silencing of the magnetic field generated by experimental model of double-circuit power transmission line with a suspension of wires of the «Barrel» type in a five-story residential building. Figure 2 shows the spatial arrangement of the transmission line model and the model of a five-story residential building.

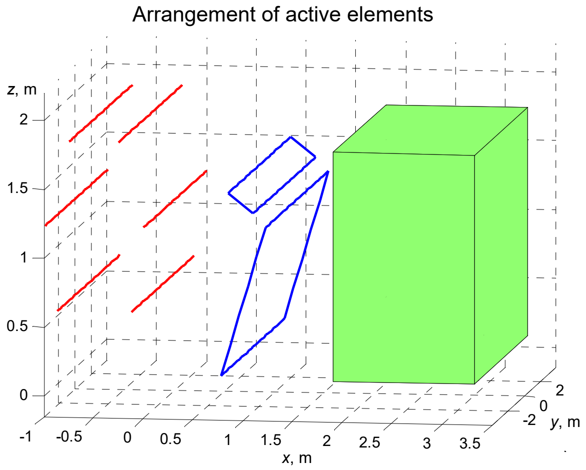

Fig. 2. Spatial arrangement of the transmission line model and the model of a five-story residential building

In the process of designing of optimal spatial arrangement and angular position of magnetic field sensors, the spatial arrangement of the two silencing windings was also designed. The spatial position of these two windings are also shown in Fig. 2.

Figure 3 shows the spatio-temporal characteristics (STC) of the initial magnetic field (1), magnetic field generated by both silencing windings (2) and the resulting magnetic field (3) with the active silencing system turned on. These spatio-temporal characteristics are calculated at the point of optimal spatial arrangement of magnetic field sensors.

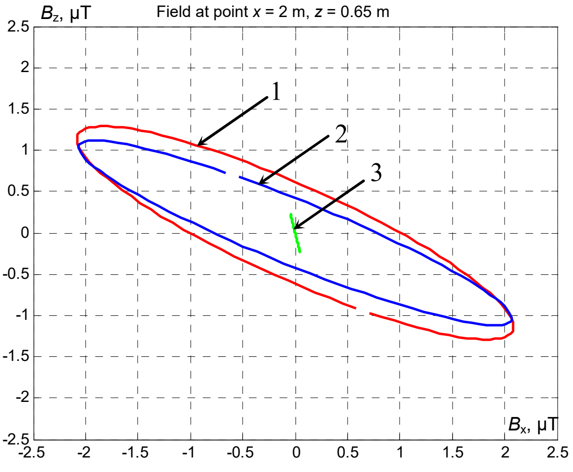

Fig. 3. The spatio-temporal characteristics of the magnetic field

From this figure it follows that with the help of two silencing windings, a sufficiently high value of the silencing factor is realized at the point of the spatial location of the of magnetic field sensors.

Experimental studies. To conduct experimental research, a model of a double-circuit power transmission line with a wire suspension of the «Barrel» type developed, the photo of which shown in Fig. 4.

Fig. 4. Power transmission line model with a wire suspension of the «Barrel» type

A model of a double-circuit system of active silencing with two silencing windings has also been developed, a photo of which is shown in Fig. 5.

To control the currents in the silencing windings and the implementation of the regulators, the system of active silencing model was developed, the photo of which is shown in Fig. 6.

Fig. 5. Two compensating silencing of double-circuit system of active silencing model

Fig. 6. Double-circuit system of active silencing model

Next to the two magnetic field sensors, photo of which shown in Fig. 7. With the help of which a closed-loop control algorithm for two silencing windings implemented, sensors are also installed, with the help of which the STC of the MF is measured.

The sensors mounted on tripods, with the help of which it is possible to set the required positioning angles of the magnetic field sensors.

Fig. 7. Magnetic field sensors

Results of experimental studies. Let us consider the first variant of the angular position of the magnetic field sensors. Both sensors are installed orthogonally to the X and Z coordinate axes. On Fig. 8 shows the experimental silencing factor surface. The silencing factor is greater than 5.

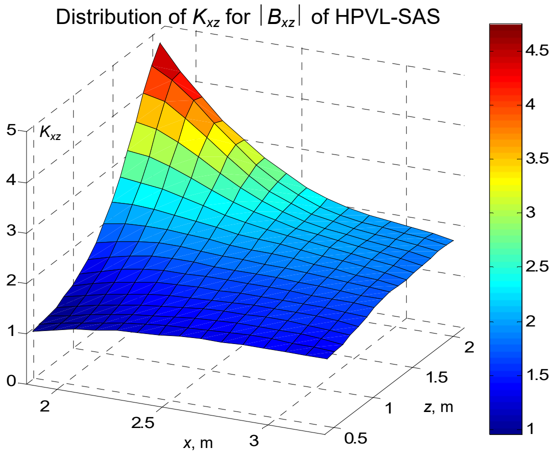

Fig. 8. Experimental silencing factor surface for first variant

Consider now the second variant of the angular position of the magnetic field sensors. The sensors are installed in such a way that their outputs have the maximum voltage when only one silencing winding of the same channel is operating. In this case, the angular positions of the sensors are respectively equal to 113 degrees and 358 degrees. On Fig. 9 shows the experimental silencing factor surface.

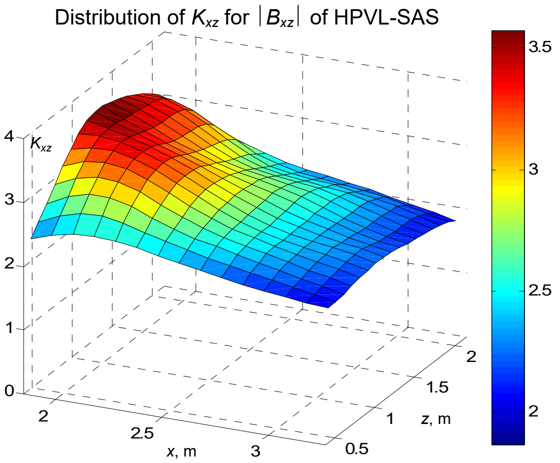

Fig. 9. Experimental silencing factor surface for second variant

The silencing factor is greater than 3.5. With such an installation of the magnetic field sensors, each channel most effectively suppresses the induction of the initial magnetic field in the plane in which this channel generates the magnetic field.

Consider now the third variant of the angular position of the magnetic field sensors. The sensors are installed in such a way that their outputs have a minimum voltage when only one silencing winding of another channel is operating. In this case, the angular positions of the sensors are respectively equal to 222 degrees and 187 degrees. Figure 10 shows the experimental silencing factor surface.

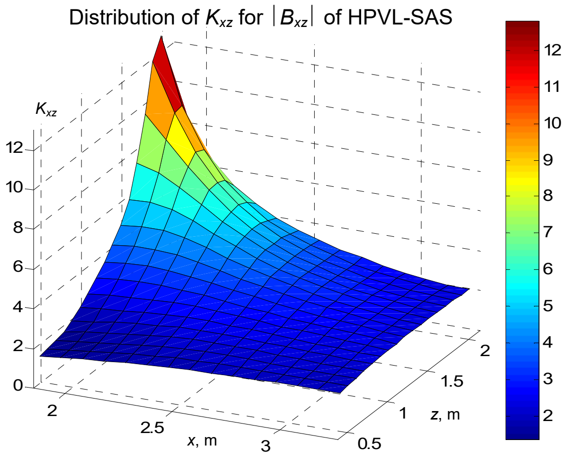

Fig. 10. Experimental silencing factor surface for third variant

The experimental silencing factor is greater than 12. With such an installation of the magnetic field sensors, each channel most effectively suppresses the induction of the initial magnetic field in a plane orthogonal to the plane in which the other channel generates the magnetic field. Therefore, the channels have minimal influence on each other when they work together.

Conclusions.

1. A method for optimizing the spatial arrangement and angular position of magnetic field sensors in a closed system of active silencing of the magnetic field to ensure maximum efficiency of active silencing of the magnetic field created by overhead power lines has been developed.
2. Optimization of the spatial arrangement and angular position of the magnetic field sensors according to the developed method is reduced to the calculation of the solution of the vector minimax optimization problem based on binary preference relations. The objective function vector of the minimax optimization problem and the calculation of constraints are formed on the basis of the Biot–Savart law and this solution is calculated on the basis of stochastic nonlinear algorithms of Archimedes.
3. Based on the developed method, the optimal spatial arrangements and angular positions of two magnetic field sensors, as well as currents in two silencing windings for double-circuit systems of active jamming of the magnetic field in a multi-storey old house, created by double-circuit overhead power lines 110 kV with a «Barrel» type arrangement of wires.
4. The effectiveness of the developed method for optimizing the spatial arrangement and angular position of two magnetic field sensors has been experimentally confirmed on a physical model of a system for active silencing of a magnetic field with a double-circuit power transmission line with a «Barrel» type arrangement of wires, which made it possible to reduce the level of the

magnetic field with an initial induction of 5.7 μT to safe level for the population with an induction of 0.5 μT.

Acknowledgment. The authors express their gratitude to the engineers Sokol A.V. and Shevchenko A.P. of the department of magnetism of technical object of Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine for the creative approach and courage shown during the creation under fire, under martial law, of an experimental installation and successful testing of a laboratory model of the system of active silencing.

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

REFERENCES

1. Sung H., Ferlay J., Siegel R.L., Laversanne M., Soerjomataram I., Jemal A., Bray, F. Global Cancer Statistics 2020: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries. *CA: A Cancer Journal for Clinicians*, 2021, vol. 71, no. 3, pp. 209-249. doi: https://doi.org/10.3322/caac.21660.

2. *Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields)*. Available at: http://data.europa.eu/eli/dir/2013/35/oj (Accessed 25.07.2022).

3. *The International EMF Project. Radiation & Environmental Health Protection of the Human Environment World Health Organization*. Geneva, Switzerland, 1996. 2 p. Available at: https://www.who.int/initiatives/the-international-emf-project (Accessed 25.07.2022).

4. Rozov V.Yu., Grinchenko V.S., Yerisov A.V., Dobrodeyev P.N. Efficient shielding of three-phase cable line magnetic field by passive loop under limited thermal effect on power cables. *Electrical Engineering & Electromechanics*, 2019, no. 6, pp. 50-54. doi: https://doi.org/10.20998/2074-272x.2019.6.07.

5. Rozov V.Y., Pelevin D.Y., Pielievina K.D. External magnetic field of urban transformer substations and methods of its normalization. *Electrical Engineering & Electromechanics*, 2017, no. 5, pp. 60-66. doi: https://doi.org/10.20998/2074-272X.2017.5.10.

6. Rozov V.Yu., Reutskyi S.Yu., Pelevin D.Ye., Kundius K.D. Approximate method for calculating the magnetic field of 330-750 kV high-voltage power line in maintenance area under voltage. *Electrical Engineering & Electromechanics*, 2022, no. 5, pp. 71-77. doi: https://doi.org/10.20998/2074-272X.2022.5.12.

7. Rozov V.Yu., Kundius K.D., Pelevin D.Ye. Active shielding of external magnetic field of built-in transformer substations. *Electrical Engineering & Electromechanics*, 2020, no. 3, pp. 24-30. doi: https://doi.org/10.20998/2074-272x.2020.3.04.

8. Salceanu A., Paulet M., Alistar B.D., Asiminicesei O. Upon the contribution of image currents on the magnetic fields generated by overhead power lines. *2019 International Conference on Electromechanical and Energy Systems (SIELMEN).* 2019. doi: https://doi.org/10.1109/sielmen.2019.8905880.

9. Del Pino Lopez J.C., Romero P.C. Influence of different types of magnetic shields on the thermal behavior and ampacity of underground power cables. *IEEE Transactions on Power Delivery*, Oct. 2011, vol. 26, no. 4, pp. 2659-2667. doi: https://doi.org/10.1109/tpwrd.2011.2158593.

10. Hasan G.T., Mutlaq A.H., Ali K.J. The Influence of the Mixed Electric Line Poles on the Distribution of Magnetic Field. *Indonesian Journal of Electrical Engineering and Informatics (IJEEI)*, 2022, vol. 10, no. 2, pp. 292-301. doi: https://doi.org/10.52549/ijeei.v10i2.3572.

11. Victoria Mary S., Pugazhendhi Sugumaran C. Investigation on magneto-thermal-structural coupled field effect of nano coated 230 kV busbar. *Physica Scripta*, 2020, vol. 95, no. 4, art. no. 045703. doi: https://doi.org/10.1088/1402-4896/ab6524.

12. Ippolito L., Siano P. Using multi-objective optimal power flow for reducing magnetic fields from power lines. *Electric Power Systems Research*, 2004, vol. 68, no. 2, pp. 93-101. doi: https://doi.org/10.1016/S0378-7796(03)00151-2.

13. Barsali S., Giglioli R., Poli D. Active shielding of overhead line magnetic field: Design and applications. *Electric Power Systems Research*, May 2014, vol. 110, pp. 55-63. doi: https://doi.org/10.1016/j.epsr.2014.01.005.

14. Bavastro D., Canova A., Freschi F., Giaccone L., Manca M. Magnetic field mitigation at power frequency: design principles and case studies. *IEEE Transactions on Industry Applications*, May 2015, vol. 51, no. 3, pp. 2009-2016. doi: https://doi.org/10.1109/tia.2014.2369813.

15. Beltran H., Fuster V., García M. Magnetic field reduction screening system for a magnetic field source used in industrial applications. *9 Congreso Hispano Luso de Ingeniería Eléctrica (9 CHLIE)*, Marbella (Málaga, Spain), 2005, pp. 84-99. Available at: https://www.researchgate.net/publication/229020921_Magnetic_field_reduction_screening_system_for_a_magnetic_field_source_used_in_industrial_applications (Accessed 22.06.2021).

16. Bravo-Rodríguez J., Del-Pino-López J., Cruz-Romero P. A Survey on Optimization Techniques Applied to Magnetic Field Mitigation in Power Systems. *Energies*, 2019, vol. 12, no. 7, p. 1332. doi: https://doi.org/10.3390/en12071332.

17. Canova A., del-Pino-López J.C., Giaccone L., Manca M. Active Shielding System for ELF Magnetic Fields. *IEEE Transactions on Magnetics*, March 2015, vol. 51, no. 3, pp. 1-4. doi: https://doi.org/10.1109/tmag.2014.2354515.

18. Canova A., Giaccone L. Real-time optimization of active loops for the magnetic field minimization. *International Journal of Applied Electromagnetics and Mechanics*, Feb. 2018, vol. 56, pp. 97-106. doi: https://doi.org/10.3233/jae-172286.

19. Canova A., Giaccone L., Cirimele V. Active and passive shield for aerial power lines. *Proc. of the 25th International Conference on Electricity Distribution (CIRED 2019)*, 3-6 June 2019, Madrid, Spain. Paper no. 1096. Available at: https://www.cired-repository.org/handle/20.500.12455/290 (Accessed 28 May 2021).

20. Canova A., Giaccone L. High-performance magnetic shielding solution for extremely low frequency (ELF) sources. *CIRED - Open Access Proceedings Journal*, Oct. 2017, vol. 2017, no. 1, pp. 686-690. doi: https://doi.org/10.1049/oap-cired.2017.1029.

21. Celozzi S. Active compensation and partial shields for the power-frequency magnetic field reduction. *2002 IEEE International Symposium on Electromagnetic Compatibility*, Minneapolis, MN, USA, 2002, vol. 1, pp. 222-226. doi: https://doi.org/10.1109/isemc.2002.1032478.

22. Celozzi S., Garzia F. Active shielding for power-frequency magnetic field reduction using genetic algorithms optimization. *IEE Proceedings - Science, Measurement and Technology*, 2004, vol. 151, no. 1, pp. 2-7. doi: https://doi.org/10.1049/ip-smt:20040002.

23. Celozzi S., Garzia F. Magnetic field reduction by means of active shielding techniques. *WIT Transactions on Biomedicine and Health*, 2003, vol. 7, pp. 79-89. doi: https://doi.org/10.2495/ehr030091.

24. Martynenko G. Analytical Method of the Analysis of Electromagnetic Circuits of Active Magnetic Bearings for Searching Energy and Forces Taking into Account Control Law. *2020 IEEE KhPI Week on Advanced Technology (KhPIWeek)*, 2020, pp. 86-91. doi: https://doi.org/10.1109/KhPIWeek51551.2020.9250138.

25. Martynenko G., Martynenko V. Rotor Dynamics Modeling for Compressor and Generator of the Energy Gas Turbine Unit with Active Magnetic Bearings in Operating Modes. *2020 IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP)*, 2020, pp. 1-4. doi: https://doi.org/10.1109/PAEP49887.2020.9240781.

26. Buriakovskyi S.G., Maslii A.S., Pasko O.V., Smirnov V.V. Mathematical modelling of transients in the electric drive of the switch – the main executive element of railway automation. *Electrical Engineering & Electromechanics*, 2020, no. 4, pp. 17-23. doi: https://doi.org/10.20998/2074-272X.2020.4.03.

27. Ostroverkhov M., Chumack V., Monakhov E., Ponomarev A. Hybrid Excited Synchronous Generator for Microhydropower Unit. *2019 IEEE 6th International Conference on Energy Smart Systems (ESS)*, Kyiv, Ukraine, 2019, pp. 219-222. doi: https://doi.org/10.1109/ess.2019.8764202.

28. Ostroverkhov M., Chumack V., Monakhov E. Ouput Voltage Stabilization Process Simulation in Generator with Hybrid Excitation at Variable Drive Speed. *2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering (UKRCON)*, Lviv, Ukraine, 2019, pp. 310-313. doi: https://doi.org/10.1109/ukrcon.2019.8879781.

29. Tytiuk V., Chornyi O., Baranovskaya M., Serhiienko S., Zachepa I., Tsvirkun L., Kuznetsov V., Tryputen N. Synthesis of a fractional-order $PI^{\lambda}D^{\mu}$-controller for a closed system of switched reluctance motor control. *Eastern-European Journal of Enterprise Technologies*, 2019, no. 2 (98), pp. 35-42. doi: https://doi.org/10.15587/1729-4061.2019.160946.

30. Zagirnyak M., Serhiienko S., Chornyi O. Innovative technologies in laboratory workshop for students of technical specialties. *2017 IEEE First Ukraine Conference on Electrical and Computer Engineering (UKRCON)*, 2017, pp. 1216-1220. doi: https://doi.org/10.1109/UKRCON.2017.8100446.

31. Chornyi O., Serhiienko S. A virtual complex with the parametric adjustment to electromechanical system parameters. *Technical Electrodynamics*, 2019, pp. 38-41. doi: https://doi.org/10.15407/techned2019.01.038.

32. Shchur I., Kasha L., Bukavyn M. Efficiency Evaluation of Single and Modular Cascade Machines Operation in Electric Vehicle. *2020 IEEE 15th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET)*, Lviv-Slavske, Ukraine, 2020, pp. 156-161. doi: https://doi.org/10.1109/tcset49122.2020.235413.

33. Shchur I., Turkovskyi V. Comparative Study of Brushless DC Motor Drives with Different Configurations of Modular Multilevel Cascaded Converters. *2020 IEEE 15th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET)*, Lviv-Slavske, Ukraine, 2020, pp. 447-451. doi: https://doi.org/10.1109/tcset49122.2020.235473.

34. Ostroumov I., Kuzmenko N., Sushchenko O., Pavlikov V., Zhyla S., Solomentsev O., Zaliskyi M., Averyanova Y., Tserne E., Popov A., Volosyuk V., Ruzhentsev N., Dergachov K., Havrylenko O., Kuznetsov B., Nikitina T., Shmatko O. Modelling and simulation of DME navigation global service volume. *Advances in Space Research*, 2021, vol. 68, no. 8, pp. 3495-3507. doi: https://doi.org/10.1016/j.asr.2021.06.027.

35. Averyanova Y., Sushchenko O., Ostroumov I., Kuzmenko N., Zaliskyi M., Solomentsev O., Kuznetsov B., Nikitina T., Havrylenko O., Popov A., Volosyuk V., Shmatko O., Ruzhentsev N., Zhyla S., Pavlikov V., Dergachov K., Tserne E. UAS cyber security hazards analysis and approach to qualitative assessment. In: Shukla S., Unal A., Varghese Kureethara J., Mishra D.K., Han D.S. (eds) *Data Science and Security. Lecture Notes in Networks and Systems*, 2021, vol. 290, pp. 258-265. Springer, Singapore. doi: https://doi.org/10.1007/978-981-16-4486-3_28.

36. Zaliskyi M., Solomentsev O., Shcherbyna O., Ostroumov I., Sushchenko O., Averyanova Y., Kuzmenko N., Shmatko O., Ruzhentsev N., Popov A., Zhyla S., Volosyuk V., Havrylenko O., Pavlikov V., Dergachov K., Tserne E., Nikitina T., Kuznetsov B. Heteroskedasticity analysis during operational data processing of radio electronic systems. In: Shukla S., Unal A., Varghese Kureethara J., Mishra D.K., Han D.S. (eds) *Data Science and Security. Lecture Notes in Networks and Systems*, 2021, vol. 290, pp. 168-175. Springer, Singapore. doi: https://doi.org/10.1007/978-981-16-4486-3_18.

37. Shmatko O., Volosyuk V., Zhyla S., Pavlikov V., Ruzhentsev N., Tserne E., Popov A., Ostroumov I., Kuzmenko N., Dergachov K., Sushchenko O., Averyanova Y., Zaliskyi M., Solomentsev O., Havrylenko O., Kuznetsov B., Nikitina T. Synthesis of the optimal algorithm and structure of contactless optical device for estimating the parameters of statistically uneven surfaces. *Radioelectronic and Computer Systems*, 2021, no. 4, pp. 199-213. doi: https://doi.org/10.32620/reks.2021.4.16.

38. Volosyuk V., Zhyla S., Pavlikov V., Ruzhentsev N., Tserne E., Popov A., Shmatko O., Dergachov K., Havrylenko O., Ostroumov I., Kuzmenko N., Sushchenko O., Averyanova Yu., Zaliskyi M., Solomentsev O., Kuznetsov B., Nikitina T. Optimal Method for Polarization Selection of Stationary Objects Against the Background of the Earth’s Surface. *International Journal of Electronics and Telecommunications*, 2022, vol. 68, no. 1, pp. 83-89. doi: https://doi.org/10.24425/ijet.2022.139852.

39. Gal’chenko V.Y., Vorob’ev M.A. Structural synthesis of attachable eddy-current probes with a given distribution of the probing field in the test zone. *Russian Journal of Nondestructive Testing*, Jan. 2005, vol. 41, no. 1, pp. 29-33. doi: https://doi.org/10.1007/s11181-005-0124-7.

40. Halchenko V.Y., Ostapushchenko D.L., Vorobyov M.A. Mathematical simulation of magnetization processes of arbitrarily shaped ferromagnetic test objects in fields of given spatial configurations. *Russian Journal of Nondestructive Testing*, Sep. 2008, vol. 44, no. 9, pp. 589-600. doi: https://doi.org/10.1134/S1061830908090015.

41. Ostroumov I., Kuzmenko N., Sushchenko O., Zaliskyi M., Solomentsev O., Averyanova Y., Zhyla S., Pavlikov V., Tserne E., Volosyuk V., Dergachov K., Havrylenko O., Shmatko O., Popov A., Ruzhentsev N., Kuznetsov B., Nikitina T. A probability estimation of aircraft departures and arrivals delays. In: Gervasi O. et al. (eds) *Computational Science and Its Applications – ICCSA 2021. ICCSA 2021. Lecture Notes in Computer Science*, vol. 12950, pp. 363-377. Springer, Cham. doi: https://doi.org/10.1007/978-3-030-86960-1_26.

42. Chystiakov P., Chornyi O., Zhautikov B., Sivyakova G. Remote control of electromechanical systems based on computer simulators. *2017 International Conference on Modern Electrical and Energy Systems (MEES)*, Kremenchuk, Ukraine, 2017, pp. 364-367. doi: https://doi.org/10.1109/mees.2017.8248934.

43. Zagirnyak M., Bisikalo O., Chorna O., Chornyi O. A Model of the Assessment of an Induction Motor Condition and Operation Life, Based on the Measurement of the External Magnetic Field. *2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS)*, Kharkiv, 2018, pp. 316-321. doi: https://doi.org/10.1109/ieps.2018.8559564.

44. Maksymenko-Sheiko K.V., Sheiko T.I., Lisin D.O., Petrenko N.D. Mathematical and Computer Modeling of the Forms of Multi-Zone Fuel Elements with Plates. *Journal of Mechanical Engineering*, 2022, vol. 25, no. 4, pp. 32-38. doi: https://doi.org/10.15407/pmach2022.04.032.

45. Hontarovskyi P.P., Smetankina N.V., Ugrimov S.V., Garmash N.H., Melezhyk I.I. Computational Studies of the Thermal Stress State of Multilayer Glazing with Electric Heating. *Journal of Mechanical Engineering*, 2022, vol. 25, no. 1, pp. 14-21. doi: https://doi.org/10.15407/pmach2022.02.014.

46. Kostikov A.O., Zevin L.I., Krol H.H., Vorontsova A.L. The Optimal Correcting the Power Value of a Nuclear Power Plant Power Unit Reactor in the Event of Equipment Failures. *Journal of Mechanical Engineering*, 2022, vol. 25, no. 3, pp. 40-45. doi: https://doi.org/10.15407/pmach2022.03.040.

47. Rusanov A.V., Subotin V.H., Khoryev O.M., Bykov Y.A., Korotaiev P.O., Ahibalov Y.S. Effect of 3D Shape of Pump-Turbine Runner Blade on Flow Characteristics in Turbine Mode. *Journal of Mechanical Engineering*, 2022, vol. 25, no. 4, pp. 6-14. doi: https://doi.org/10.15407/pmach2022.04.006.

48. Ummels M. *Stochastic Multiplayer Games Theory and Algorithms*. Amsterdam University Press, 2010. 174 p.

49. Shoham Y., Leyton-Brown K. *Multiagent Systems: Algorithmic, Game-Theoretic, and Logical Foundations.* Cambridge University Press, 2009. 504 p.

50. Pulido G.T., Coello C.A.C. A constraint-handling mechanism for particle swarm optimization. *Proceedings of the 2004 Congress on Evolutionary Computation* (IEEE Cat. No.04TH8753), Portland, OR, USA, 2004, vol. 2, pp. 1396-1403. doi: https://doi.org/10.1109/cec.2004.1331060.

51. Zhyla S., Volosyuk V., Pavlikov V., Ruzhentsev N., Tserne E., Popov A., Shmatko O., Havrylenko O., Kuzmenko N., Dergachov K., Averyanova Y., Sushchenko O., Zaliskyi M., Solomentsev O., Ostroumov I., Kuznetsov B., Nikitina T. Statistical synthesis of aerospace radars structure with optimal spatio-temporal signal processing, extended observation area and high spatial resolution. *Radioelectronic and Computer Systems*, 2022, no. 1, pp. 178-194. doi: https://doi.org/10.32620/reks.2022.1.14.

52. Xin-She Yang, Zhihua Cui, Renbin Xiao, Amir Hossein Gandomi, Mehmet Karamanoglu. *Swarm Intelligence and Bio-Inspired Computation: Theory and Applications*, Elsevier Inc., 2013. 450 p.

53. Hashim F.A., Hussain K., Houssein E.H., Mabrouk M.S., Al-Atabany W. Archimedes optimization algorithm: a new metaheuristic algorithm for solving optimization problems. *Applied Intelligence*, 2021, vol. 51, no. 3, pp. 1531-1551. doi: https://doi.org/10.1007/s10489-020-01893-z.

Надійшла (Received) 30.09.2022
Прийнята (Accepted) 05.11.2022
Опублікована (Published) 01.07.2023

B.I. Kuznetsov[1], *Doctor of Technical Science, Professor,*
T.B. Nikitina[2], *Doctor of Technical Science, Professor,*
I.V. Bovdui[1], *PhD, Senior Research Scientist,*
O.V. Voloshko[1], *PhD, Junior Research Scientist,*
V.V. Kolomiets[2], *PhD, Assistant Professor,*
B.B. Kobylianskyi[2], *PhD, Associate Professor,*
[1] Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine,
2/10, Pozharskogo Str., Kharkiv, 61046, Ukraine,
e-mail: kuznetsov.boris.i@gmail.com (Corresponding Author)
[2] Educational scientific professional pedagogical Institute of Ukrainian Engineering Pedagogical Academy,
9a, Nosakov Str., Bakhmut, Donetsk Region, 84511, Ukraine,
e-mail: tatjana55555@gmail.com; nnppiuipa@ukr.net

How to cite this article:
Kuznetsov B.I., Nikitina T.B., Bovdui I.V., Voloshko O.V., Kolomiets V.V., Kobylianskyi B.B. Optimization of spatial arrangement of magnetic field sensors of closed loop system of overhead power lines magnetic field active silencing. *Electrical Engineering & Electromechanics*, 2023, no. 4, pp. 26-34. doi: https://doi.org/10.20998/2074-272X.2023.4.04