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MITIGATION OF MAGNETIC FIELD FROM OVERHEAD POWER LINES WITH TRIANGULAR CONDUCTOR ARRANGEMENTS USING ACTIVE SHIELDING SYSTEMS

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Abstract: The paper presents results of synthesis, theoretical, and experimental studies of a robust system of active shielding of the magnetic field generated by overhead power lines with triangular conductor arrangements. The synthesis is based on the solution of a multi-criteria stochastic game, in which the vector payoff is calculated on the basis of the Maxwell equations solutions in a quasi-stationary approximation. The solution to the game is based on the algorithms of stochastic multiagent particle multiswarm optimization. The possibility of a significant mitigation of magnetic flux density and a reduction in the sensitivity of the system to the plant parameters uncertainty is shown. Three shielding coils are required to shield a magnetic field in a five-story building, and two shielding coils are sufficient to shield the same magnetic field in a single-story building. Practical recommendations are given on the reasonable choice of the spatial arrangements of the shielding coils of a robust system of active shielding of the magnetic field generated by an overhead power line with a triangular arrangement of conductors. The experimental research into the robust system of active shielding model of the magnetic field generated by overhead power lines with a triangular arrangement of conductors and two shielding coils is carried out. The comparison of experimental and calculated results of the magnetic flux density values in the shielding space shows that their spread does not exceed 30 %.

Key words: overhead power lines, power-frequency magnetic field, robust system of active shielding.

1. Introduction

Overhead power lines (OPL) are one of the most dangerous for people sources of technogenic power-frequency (PF) magnetic field (MF). The World Health Organization experts have identified the carcinogenic properties of the PF MF. Therefore, in the world for the last 15 years, the sanitary standards for the maximum permissible level of magnetic flux density at a frequency of 50–60 *Hz* have been constantly increasing, and intensive research intended to develop methods for MF normalization has been carried out.

Active contour shielding of the PF MF generated by OPLs [1–10] is the most acceptable and economically feasible for ensuring the sanitary norms of Ukraine on the PF MF [11–12].

Methods for the synthesis of active shielding systems (SAS) for the MF generated by OPLs have been developed in [13–24]. The SAS consists of a shielding coil (SC), which forms a compensating MF. Currents in the SC are automatically generated as a function of the signal from the MF sensors is installed in the shielding space. For the power supply, the SAS contains a current source that receives energy from an external source.

Initial data for the synthesis of the system are the parameters of transmission lines (working currents, geometry and number of wires, location of the OPLs relative to the shielding space) and the dimensions of the shielding space, and the standard value of the magnetic flux density, which should be achieved by shielding. The purpose of the SAS synthesis is to determine the parameters of the SC (quantity, configuration, spatial arrangement, currents) and the resulting values of magnetic flux density in the shielding space.

Single-circuit OPLs with horizontal and vertical bus arrangement, double-circuit OPLs such as “barrel”, “fir-tree” and “inverted fir-tree”, and groups of OPLs generate a MF with a weak polarization. The space-time characteristics (STC) of such an MF is a very elongated ellipse whose ellipticity coefficient (the ratio of the smaller axis to the larger axis) is practically zero. A single SC of a single-circuit SAS generates a MF, whose STC is a straight line. The single-circuit SAS with a single SC compensates the larger axis of the STC ellipse of the initial MF, so that the STC of the total MP with SAS is significantly smaller than the STC of the initial MF that provides a high shielding factor of such single-circuit SASs. That is why using a single-circuit SAS containing a single SC can effectively shield a MF with low polarization. For this reason, they are widely used in the world’s OPLs [2].

However, single-circuit OPLs with a triangular conductors arrangement generate a highly polarized MF, so the STC of such a MF is practically circular. Therefore, for such an MF to be shielded effectively, it is necessary to have at least two SCs [5].

The purpose of this work is to synthesize systems of active shielding of the magnetic field at power frequency generated by overhead power lines with a triangular arrangement of conductors.

2. Problem Statement

In the synthesis of the SAS, the mathematical model of the initial MF is known inaccurately [25]. In particular, currents in conductors that have daily, weekly, seasonal variations resulting in changing the position of the STC of the original MF generated by the power lines are approximately known. The geometric dimensions of the SC, the parameters of the regulators, etc. are approximated. Therefore, we introduce a vector of uncertainty of the system parameters δ, which is equal to the deviation of the real parameters of the system from their nominal values used in the synthesis of the system. The problem of synthesizing a robust SAS is reduced to the determination of such a vector X of spatial arrangement and geometric sizes of a SC, as well as the parameters of the regulator and the uncertainty parameters vector δ, at which the maximum value of the magnetic flux density at selected points P_j of the shielding space P assumes a minimum value for the vector X but the maximum value for the vector δ. This technique corresponds to the standard approach to the synthesis of robust systems for the worst-case [25] when the uncertainty parameters vector δ leads to the greatest deterioration in the compensation of the initial MF created by OPL.

This problem can be formulated in the form of the following multi-criteria game [16] with a vector payoff

$$B(X,\delta)=\left[B(X,\delta,P_1),B(X,\delta,P_2)\ldots \right. \\ \left. \ldots B(X,\delta,P_m)\right]^T, \quad (1)$$

the components of which $B(X,\delta,P_i)$ are the magnetic flux density in the m points P_i of the shielding space. This is the case when the constraints on the control vector and the variables of the SAS state, and the vector of uncertainty parameters must be taken into account.

In multi-criteria game (1), the first player is the vector X of spatial arrangement and geometric sizes of SC, as well as parameters of the regulator and its strategy is the minimization of the vector payoff (1), and the second player is the vector δ of uncertainty parameters, and the strategy of this player is maximization of the same vector payoff [25–27].

Note that the components of the vector payoff (2) are nonlinear functions of the vector of spatial arrangement and geometric sizes of SC, as well as the parameters of the regulator X and uncertainty parameters vector δ are calculated on the basis of the Maxwell equations solutions in the quasi-stationary approximation [28–36].

Solution algorithm. Consider the algorithm for finding a solution to the game. To find the solution to multi-criterion game (1) from Pareto-optimal solutions taking into account the binary preference relations [37], we used the particle multiswarm optimization (PSO) algorithm [38–39], in which the number of swarms is equal to the number of components m of payoff vector (1).

In the standard particle swarm optimization algorithm, particle velocities are changed according to linear laws [37–49]. To increase the speed of finding the global solution, special nonlinear algorithms of stochastic multi-agent optimization have been recently proposed in [50]. The motion of the i-th particle of the j-th swarm is described by the following expressions

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

$$\begin{aligned} u_{ij}(t+1) &= w_{2j}u_{ij}(t)+c_{3j}r_{3j}(t)H*\ldots \\ &\ldots*\left(p_{3ij}(t)-\varepsilon_{3ij}(t)\right)\left[z_{ij}(t)-\delta_{ij}(t)\right]+\ldots \\ &\ldots+c_{4j}r_{4j}(t)H\left(p_{4ij}(t)-\varepsilon_{4ij}(t)\right)*\ldots \\ &\ldots*\left[z_j^*(t)-\delta_{ij}(t)\right] \end{aligned} . \quad (3)$$

$$\begin{aligned} x_{ij}(t+1) &= x_{ij}(t)+v_{ij}(t+1), \\ \delta_{ij}(t+1) &= \delta_{ij}(t)+u_{ij}(t+1) \end{aligned}, \quad (4)$$

where $x_{ij}(t)$, $\delta_{ij}(t)$ and $v_{ij}(t)$, $u_{ij}(t)$ is the position and velocity of the i-th particle of the j-th swarm.

In (2) – (4), $y_{ij}(t)$, $z_{ij}(t)$ and $y_j^*(t)$, $z_j^*(t)$ are the best local and global positions of the i-th particle, found by only one i-th particle and all the particles of the j-th swarm, respectively Moreover, the best local position $y_{ij}(t)$ and global position $y_j^*(t)$ of the i-th particle of the j-th swarm are understood in terms of the first player strategy $x_{ij}(t)$ for a minimum of components $B(X,\delta,P_i)$ of payoff vector (1). However, the best local position $z_{ij}(t)$ and global position $z_j^*(t)$ of the i-th particle of the j-th swarm are understood in terms of the second player strategy $\delta_{ij}(t)$ for a maximum of the same components $B(X,\delta,P_j)$ of payoff vector (1).

Four independent random numbers $r_{1j}(t)$, $r_{2j}(t)$, $r_{3j}(t)$, $r_{4j}(t)$ are in the range of [0,1], which determine the stochastic particle velocity components.

Positive constants c_{1j}, c_{2j} and c_{3j}, c_{4j} determine the cognitive and social weights of the particle velocity components.

The Heaviside function H is used as a function of switching the motion of a particle according to the local $y_{ij}(t)$, $z_{ij}(t)$ and global $y_j^*(t)$, $z_j^*(t)$ optimum.

The switching parameters of the cognitive p_{1ij}, p_{3ij} and social p_{2ij}, p_{4ij} components of the particle velocity to the local and global optimums are taken in the form of increments of changes in payoff (1) for players' strategies $x_{ij}(t)$, $\delta_{ij}(t)$ when moving to the local and global optimums, respectively.

The random numbers $\varepsilon_{1ij}(t)$, $\varepsilon_{2ij}(t)$, $\varepsilon_{3ij}(t)$ and $\varepsilon_{4ij}(t)$ determine the parameters of switching the motion of a particle to local and global optimums, respectively.

To improve the quality of the solution finding process, the inertia coefficients w_{1j}, w_{2j} are used.

3. Computer simulation

Consider the result of the synthesis of a robust SAS of the MF created by OPLs with a triangular arrangement of phase conductors. Figure 1 shows the location of a single-circuit 110 k*V* OPL with a triangular arrangement of phase conductors that generates a MF, the magnetic flux density level of which must be mitigated in the shielding zone.

Fig. 1. The location of a 110 kV overhead power line with triangular phase conductors arrangements.

For the synthesis of an SAS, in addition to the geometric dimensions of the transmission lines and the shielding zone, the values of the currents in the bus of the entire OPL are required. For this purpose, first, experimental studies of the magnetic field level were carried out both in the shielding zone and near the transmission lines. Based on the experimental data obtained, the problem of current identification in the phase conductors of OPL is solved, in which the sum of the squares of errors between the measured and model levels of magnetic flux density at given points is minimized.

Let us first consider the results of the SAS initial MF in a five-story building, located within 15 *m* distance from the OPL. Actually, the current of a 110 k*V* overhead triangular single-circuit line is 200–500 A. We perform the SAS synthesis for the worst case with OPL current of 1000 *A*, which is more than double the real OPL current. Then the initial magnetic flux density in the shielding space is 4 μ*T*, which is 8 times higher than the sanitary norms. To compensate for this MF in the shielding space, three SC are required.

On the basis of the MF model created by the OPL, the problem of synthesis of a robust SAS having three square-shaped SC has been solved. The coordinates of the winding angles in Figs. 2, 5, 7, *a*, 8 are shown along the axes 0X, and 0Z, directed vertically (while the axis 0Y is directed along the OPL). Figure 2 shows the location of the compensating windings with the coordinates of the upper parts of the windings (5, 15), (11, 14.5), (5, 6), and the coordinates of the lower parts of the windings – (9, 0.5), (5, -1.5), (10, 7.5). For compensating windings, the calculated values of ampere-turns (*A*turns*) necessary to create the calculated value of the magnetic flux density are determined; they are equal to 177 *A*turns*, 195 *A*turns* and 199 *A*turns*, respectively.

Table 1 shows the magnetic flux density values for the optimal system and for the robust system at nominal parameter values (δ =0) with the worst-case combination [5]. In a robust system, the maximum magnetic flux density value in the shielding space does not exceed 0.5 μ*T*, which corresponds to the sanitary standards of Ukraine.

For the worst-case, when in the parameters variations vector δ lead to the greatest deterioration in the compensation of the original MF by the robust system, the maximum magnetic flux density value in the shielding space does not exceed increases by 10 % compared to the robust system at nominal parameters values when (δ =0).

Despite the fact that in the original system at nominal parameters values when (δ =0), the maximum magnetic flux density value in the shielding space is approximately by 10 % less than in the robust system, and is equal to 0.4 μT. However, for the worst-case when the variable parameters vector changes, the maximum magnetic flux density value in the shielding space for the optimal system increases to 0.6 μ*T*.

Table 1

	Optimal system	Robust system
Nominal parameters values (δ =0)	0,4 μT	0,45 μT
Worst-case	0,6 μT	0,5 μT

Note that the SC position of the robust system shown in Fig. 1 slightly differes from the position of the SC of the optimal system, but due to such differences, the synthesized robust SAS allows reducing the system sensitivity to the plant parametres uncertainties.

Fig. 2 shows the resultant magnetic flux density isolines with the SAS is on. As can be seen from Fig. 2, the minimum magnetic flux density value in the shielding zone is 0.5 µ*T*. The initial MF generated by the OPL in the shielding zone exceeds the level of 2 µ*T* and, therefore, the SAS shielding factor maximum is more than 10. When the active shielding system is on, as can be seen from Fig. 2, the magnetic flux density level in the shielding zone does not exceed 0.5 µ*T*.

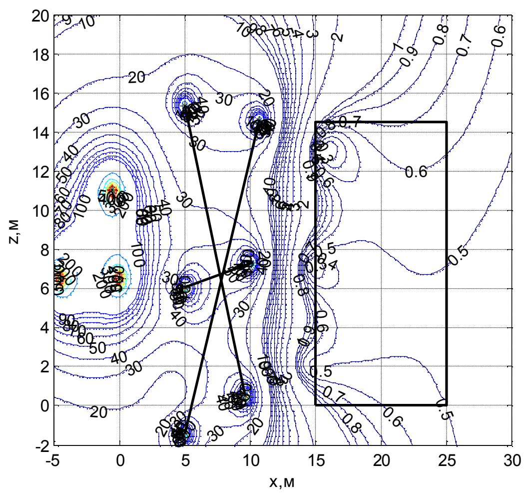


Fig. 2. Isolines of resultant magnetic flux density with the system of active shielding being on in a five-story building.

Fig. 3. shows magnetic flux density with and without the active shielding system.

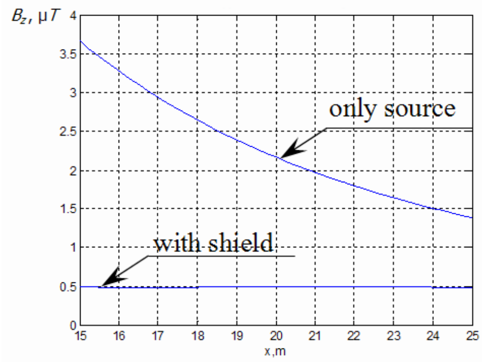


Fig. 3. Comparison of magnetic flux density with and without the system of active shielding in a five-story building.

Fig. 4 shows the STC of the MF generated by an OPL with a "triangle" type of phase conductors arrangements; SC and the total MF with the SAS is on. As can be seen from Fig. 4, the STC of the MF generated by an OPL with a triangular arrangement of conductors; and the STC of the MF generated by a SC are practically a circles. But the STC of the total MF with the SAS is on is a straight line.

Note that the STC is a hodograph and represents a line that describes the end of the magnetic flux density vector B on the plane of the magnetic flux density vector projections B_z and B_x and the axes $0Z$ and $0X$ when time changes during a period of change in the magnetic flux density vector. Naturally, this characteristic does not depend on time.

When implementing the SAS, for the SAS SC to be mounted at altitudes of 10 meters, appropriate supports are required that leads to quite large material costs.

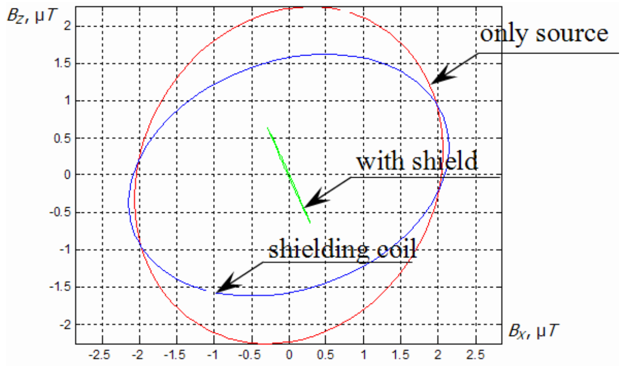


Fig. 4. Comparison of space-time characteristics of magnetic flux density with and without the system of active shielding and shielding coil in a five-story building.

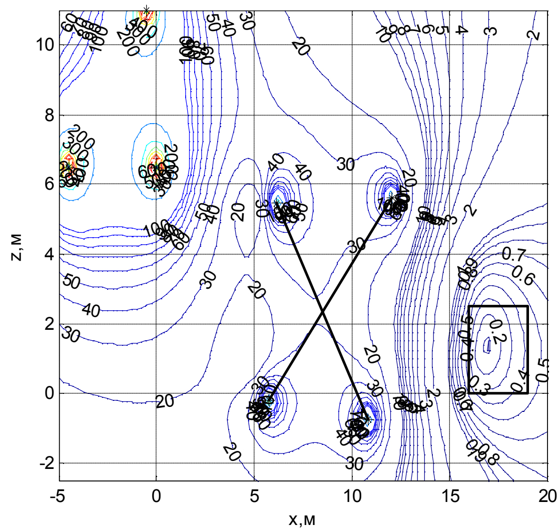


Fig. 5. Isolines of resultant magnetic flux density with the system of active shielding in a single-story building.

Let us now consider the results of the synthesis of a MF SAS in a single-story building located at a distance of 17 *m* from the OPL. The SAS contains two square-shaped SC. The upper branches of SC have the coordinates (6.5, 5.5) and (12, 5.8). The lower branches have the coordinates (12, -0.7) and (6.0, -0.5). Fig. 5 shows the isolines of the resultant magnetic flux density with the SAS in “on”-state. The minimum magnetic flux density value in the shielding space is 0.2 μ*T*, but in the entire shielding space, the magnetic flux density level does not exceed 0.5 μ*T*.

Fig. 6. shows the comparison of magnetic flux density with and without the SAS.

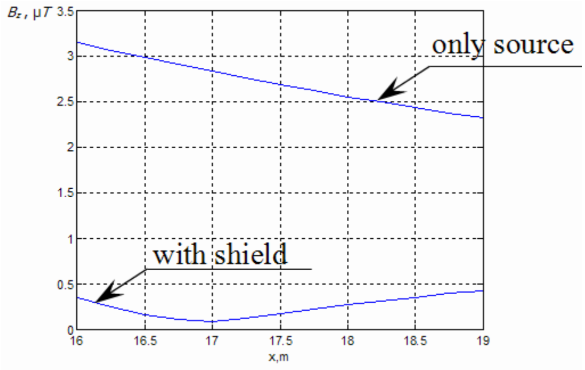
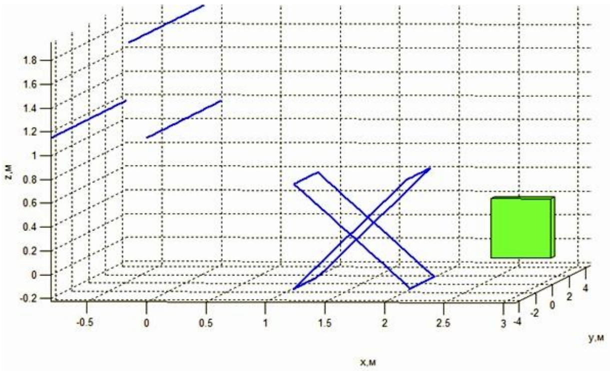


Fig. 6. Comparison of magnetic flux density with and without the system of active shielding in a single-story building.



a

b

Fig. 7. Scheme a) and a model b) of overhead power lines with triangular phase conductors arrangements, two shielding coils of the system of active shielding and shielding zone.

4. Experimental Research

Consider experimental studies of a full-scale SAS layout with two SC. For the experimental studies, a model of the OPL and SAS on a scale of 1–15 relative to a real OPL has been developed. Fig. 7 shows a scheme a) and a model b) of OPL, two SC of SAS and shielding space.

In an OPL model with 100 A current, the magnetic flux density level in the shielding zone is 2 μ*T*, which is 4 times higher than the sanitary norms. For this shielding zone, the robust SAS having two square-shaped SC is synthesized. The upper branches of the SC have the coordinates (0.6, 0.6) and (1.4, 0.65). The lower branches have the coordinates (1.5, -0.15) and (0.6, -0.18). Each SC contains 20 winds and is powered by TDA7294 amplifiers. The SAS model contains an external magnetic flux density controller and an internal current controller. An inductive sensor is used as an magnetic flux density sensor, and the magnetic flux density measurement is performed by an EMF-828 magnetometer manufactured by LUTRON [51].

Figure 8 shows isolines of the resultant magnetic flux density, with the SAS being on. The minimum magnetic flux density value in the shielding space is 0.2 μ*T*, but in the entire shielding space, the magnetic flux density level does not exceed 0.5 μ*T*.

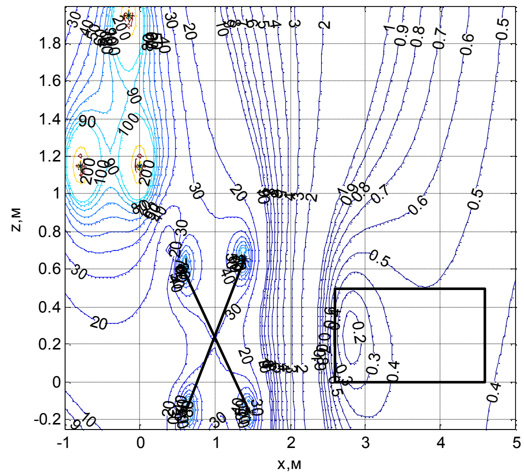


Fig. 8. Isolines of the resultant magnetic flux density with the system of active shielding being in “on”-state.

Fig. 9 shows a comparison of the magnetic flux density between experimentaly measured and simulated levels with and without the SAS. The experimentally obtained SAS shielding factor also exceeds 4 units. Here, the SAS shielding factor refers to the ratio of magnetic flux density in the shielding space with and without the SAS.

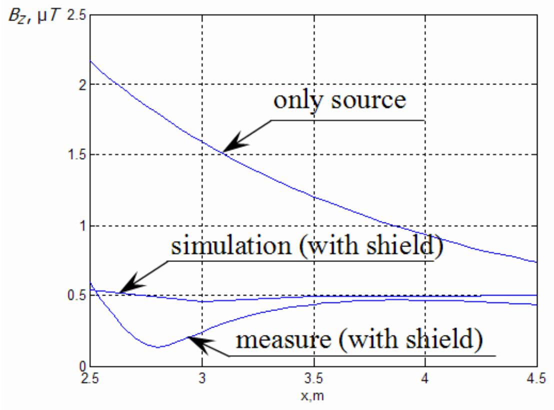


Fig. 9. Comparison of magnetic flux density between measurements and simulations with and without the system of active shielding.

5. Conclusions

1. For the first time the robust system of active shielding is synthesized for the mitigation of magnetic field generated by overhead power lines with a triangular arrangement of conductors.

2. As a result of the synthesis two variants of the system from the perspectives of practical implementation were selected. Three shielding coils are required to shield a magnetic field in a five-story building. For shielding the same magnetic field in a single-story building, two shielding coils are sufficient.

3. For the first time field experimental studies were carried out for the robust system of active shielding for the mitigation of magnetic field generated by overhead power lines with triangular conductor arrangements and two shielding coils. The comparison between experimental and calculated results of the magnetic flux density values in the shielding zone shows that their spread does not exceed 30 %.

4. The system of active shielding reduces the level of initial magnetic flux density throughout the shielding space by more than 4 units up to the Ukrainian sanitary norms level and has less sensitivity to the plant parameters uncertainty in comparison with the known systems.

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ЗНИЖЕННЯ МАГНІТНОГО ПОЛЯ ПОВІТРЯНИХ ЛЕП ІЗ ТРИКУТНИМ РОЗТАШУВАННЯМ ПРОВОДІВ ІЗ ВИКОРИСТАННЯМ АКТИВНОГО ЕКРАНУВАННЯ

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Уперше проведено синтез, теоретичні та експериментальні дослідження робастної системи активного екранування магнітного поля, яке створюється повітряними лініями електропередачі із трикутним розташуванням проводів. Синтез заснований на вирішенні багатокритеріальної стохастичної гри, в якій векторний виграш обчислюється на підставі рішень рівнянь Максвелла в квазістаціонарному наближенні.

Рішення гри знаходиться на основі алгоритмів стохастичної мультиагентної оптимізації мультіроем частинок. Показано можливість суттєвого зниження рівня індукції вихідного магнітного поля у заданому просторі і зниження чутливості системи до невизначеності параметрів системи. Для екранування магнітного поля в п'ятиповерховій будівлі необхідно три екрануючої обмотки, а для екранування того ж магнітного поля в одноповерховій будівлі досить двох екрануючих обмоток. Наведено практичні рекомендації з обгрунтованогог вибору просторового положення екрануючих обмоток робастной системи активного екранування магнітного поля, яке створюється лініями електропередачі із трикутним розташуванням проводів.

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