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ACTIVE SHIELDING OF MAGNETIC FIELD WITH CIRCULAR SPACE-TIME CHARACTERISTIC

Aim. The synthesis of two degree of freedom robust two circuit system of active shielding of magnetic field with circular space-time characteristic, generated by overhead power lines with «triangle» type of phase conductors arrangements for reducing the magnetic flux density to the sanitary standards level and to reducing the sensitivity of the system to plant parameters uncertainty. Methodology. The synthesis is based on the multi-criteria game decision, in which the payoff vector is calculated on the basis of the Maxwell equations quasi-stationary approximation solutions. The game decision is based on the stochastic particles multiswarm optimization algorithms. The initial parameters for the synthesis by system of active shielding are the location of the overhead power lines with respect to the shielding space, geometry and number of shielding coils, operating currents, as well as the size of the shielding space and magnetic flux density normative value, which should be achieved as a result of shielding. The objective of the synthesis is to determine their number, configuration, spatial arrangementand and shielding coils currents, setting algorithm of the control systems as well as the resulting of the magnetic flux density value at the shielding space. Results. Computer simulation and field experimental research results of two degree of freedom robust two circuit system of active shielding of magnetic field, generated by overhead power lines with «triangle» type of phase conductors arrangements are given. The possibility of initial magnetic flux density level reducing and system sensitivity reducing to the plant parameters uncertainty is shown. Originality. For the first time the synthesis, theoretical and experimental research of two degree of freedom robust two -circuit t system of active shielding of magnetic field generated by single-circuit overhead power line with phase conductors triangular arrangements carried out. Practical value. Practical recommendations from the point of view of the practical implementation on reasonable choice of the spatial arrangement of two shielding coils of robust two -circuit system of active shielding of the magnetic field with circular space-time characteristic generated by single-circuit overhead power line with phase conductors triangular arrangements are given. References 32, figures 17.

Key words: **overhead power lines with «triangle» type of phase conductors arrangements, magnetic field, system of active schielding, computer simulation, field experimental research.**

Цель. Синтез комбинированной робастной двухконтурной системы активного экранирования магнитного поля с круговой пространственно-временной характеристикой, генерируемого одноконтурной воздушной линией электропередачи с треугольным подвесом проводов для снижения индукции магнитного поля до уровня санитарных норм и для снижения чувствительности системы к неопределенности параметров объекта управления. Методология. Синтез основан на решении многокритериальной стохастической игры, в которой векторный выигрыш вычисляется на основании решений уравнений Максвелла в квазистационарном приближении. Решение игры находится на основе алгоритмов стохастической мультиагентной оптимизации мультироем частиц. Исходными параметрами для синтеза системы активного экранирования являются расположение высоковольтной линий электропередачи по отношению к экранируемому пространству, геометрические размеры, количество проводов и рабочие токи линии электропередачи, а также размеры экранируемого пространства и нормативное значение индукции магнитного поля, которое должно быть достигнуто в результате экранирования. Задачей синтеза является определение количества, конфигурации, пространственного расположения и токов экранирующих обмоток, алгоритма работы системы управления, а также результирующего значения индукции магнитного поля в экранируемом пространстве. Результаты. Приводятся результаты теоретических и полевых экспериментальных исследований комбинированной робастной двухконтурной системы активного экранирования магнитного поля, генерируемого воздушной линией электропередачи с треугольным подвесом проводов. Показана возможность снижения уровня индукции исходного магнитного поля внутри экранируемого пространства и снижения чувствительности системы к неопределенностям параметров объекта управления. Оригинальность. Впервые проведены синтез, теоретические и экспериментальные исследования комбинированной робастной двухконтурной системы активного экранирования магнитного поля, генерируемого одноконтурной воздушной линией электропередачи с треугольным подвесом проводов. Практическая ценность. Приводятся практические рекомендации по обоснованному выбору с точки зрения практической реализации пространственного расположения двух экранирующих обмоток двухконтурной робастной системы активного экранирования магнитного поля с круговой пространственно-временной характеристикой, создаваемого одноконтурной воздушной линией электропередачи с треугольным подвесом проводов. Библ. 32, рис. 17.

Ключевые слова: **воздушная линия электропередач, подвес проводов типа «треугольник», магнитное поле, система активного экранирования, компьютерное моделирование, полевые экспериментальные исследования.**

Introduction. Overhead power lines (OPL) are one of the most dangerous for people sources of technogenic power frequency (PF) of 50-60 Hz magnetic field (MF) [1, 2]. World Health Organization experts have identified the carcinogenic properties of the power frequency MF. Therefore, in the world over the past 15 years, sanitary standards are constantly tightening at the maximum permissible level of MF induction of 50-60 Hz. And intensive research is being conducted on the development of methods for MF normalization [3-5].

Active contour shielding of PF MF generated by OPL [3, 4] is the most acceptable and economically feasible for ensuring the sanitary norms of Ukraine in the PF MF [1, 2]. The methods of synthesis of systems of active shielding (SAS) for MF, generate by OPL, developed in [6-11]. The initial data for the synthesis of the system are the parameters of the transmission lines (working currents, geometry and number of wires, location of the transmission lines relative to the protected space) and the dimensions of the shielding space and magnetic flux density sanitary standards level, which should be achieved as a result of screening [12-22]. In the process of synthesis, it is necessary to determine the parameters of the shielding coils (SC) (their number, configuration, and spatial arrangement), currents and the resulting magnetic flux density level. To shielding factor improvement two degree of freedom SAS are used in which simultaneously used feed back regulator for closed loop control and feed forward regulator for open loop control [23-27].

Single-circuit OPL with horizontal and vertical bus arrangement, double-circuit OPL such as «barrel», «tree» and «inverted tree» [28], and groups of OPL generates a MF with a weak polarization. The space-time characteristics (STC) of such MF is a very elongated ellipse whose ellipse coefficient (ratio of the smaller axis to the larger axis) is seeks to zero. Single SC of single-circuit OPL generates MF, whose STC is a straight line. With such a single-circuit SAS with single SC, the major axis of the STS ellipse of the initial MF is compensated, so that the STS of the total MP with SAS is on is significantly smaller than the STS of the initial MF, which determines the high shielding factor of such single-circuit SAS. That is why using single-circuit SAS containing single SC can effectively shielded by MF with a small polarization. Exactly for such power lines, single-circuit SAS with single SC is most widely used in world practice [3].

However the single-circuit OPL with phase conductor's triangular arrangements generated most polarized MF. The STC of such MF is practically a circle. Therefore, for effective shielding of such MF it is necessary to have two SC at least [12]. Note that the vast majority of single-circuit OPL in Ukraine has just such phase conductors triangular arrangements.

As an example consider shielding of MF with circular STC generated by 110 kV OPL with phase conductors triangular arrangements in a single-story building located at a distance of 10 m from OPL. In Fig. 1 are shown location OPL, shielding space and shielding coils. The SAS contains two square shapes SC the spatial arrangement of which determine intuitively without SAS synthesis. In Fig. 1 also are shown this both SC. SC upper parts are coordinates (4.0, 4.0) and (8.0, 4.0). SC lower parts are coordinates (4.0, 0.0) and (8.0, 0.0). Figure 2 shows the picture of such shielding coils, the spatial arrangement of which was chosen without system synthesis. SC upper parts of both SC located at heights of 4.0 m from the ground, and the SC lower parts located at ground level.

It was assumed that, since both SC are orthogonal to each other and so such SC generate MF with STC, which also orthogonal to each other. Using such both SC you can get a high factor. However, with such SC spatial arrangement it is not possible to obtain high shielding factor. For shielding such MF with high shielding factor it is need to synthesize SAS.

The goal of this work is the synthesis of two degree of freedom robust two circuit system of active shielding of magnetic field with circular space-time characteristic, generated by overhead power lines with «triangle» type of phase conductors arrangements for reducing the magnetic flux density to the sanitary standards level and to reducing the sensitivity of the system to plant parameters uncertainty.

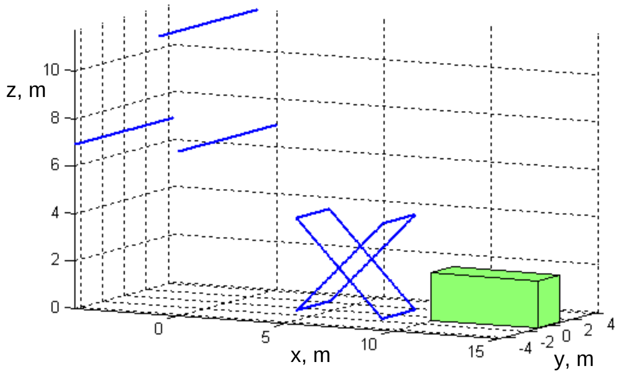

Fig. 1. The location of 110 kV overhead power line with phase conductors triangular arrangements, both shielding coils and shielding space

Fig. 2. Picture of the both shielding coil, the spatial arrangement of which were chosen without system synthesis

Problem statement. Two degree of freedom robust SAS synthesizing problem reduced [29] to the determination of such SC spatial arrangement and geometric sizes, as well as parameters of the regulator vector X and uncertainty parameters vector δ, which the maximum value of the magnetic flux density at 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 worst-case robust systems synthesis approach [27, 29], when uncertainty parameters vector δ lead to the greatest deterioration in initial MF shielding created by OPL.

Parameters of the regulator vector of two degree of freedom robust SAS includes the parameters of the feed forward regulator in form amplitude and the phase vectors of the open loop control and the parameters of the feed back regulator in form gain vectors of the closed loop control.

This two degree of freedom robust SAS synthesizing problem formulated in multi-criteria game form [30-32] with vector payoff

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

Components $B(X, \delta, P_i)$ are magnetic flux density in shielding space m points P_i. These components are nonlinear functions of the vectors X and δ calculated on basis of Maxwell equations quasi-stationary approximation solutions [5].

First player is vector X and its strategy vector payoff minimization. Second player is vector δ and this strategy is same vector payoff maximization [27, 29].

To find multi-criterion game solution from Pareto-optimal set solutions taking into account binary preference relations [30] used particle multi swarm optimization (PSO) algorithm [31], in which swarms number equal number of vector payoff components.

Computer simulation results. Consider the result of robust SAS synthesis of MF with circular space-time characteristic created by 110 kV OPL with phase conductors triangular arrangements in a single-story building located at a distance of 10 m from OPL. In Fig. 3 are shown location OPL, shielding coils and shielding space in which magnetic flux density level must mitigated to the Ukraine sanitary norms level.

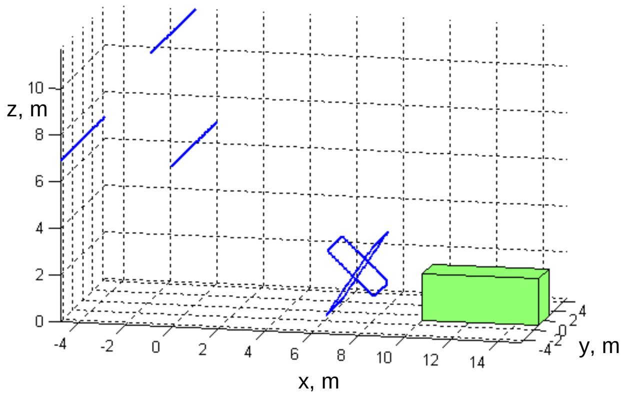

Fig. 3. The location of 110 kV overhead power line with phase conductors triangular arrangements, shielding coils and shielding space

For SAS synthesis in addition OPL geometric dimensions and shielding space the OPL bus currents values are necessary. Field experimental research of magnetic flux density level both in shielding space and near OPL carried out. In Fig. 4 are shown the isolines of the initial magnetic flux density generated by OPL with phase conductors triangular arrangements and with current of 250 A . The initial induction of the MF in shielding space is 0.8 μT, which is 1.6 times higher than the sanitary norms.

Based on the obtained experimental data, the problem of OPL phase conductor's current identification solved. MF SAS synthesis results are two square shapes SC spatial arrangement.

In Fig. 3 also are shown this both SC. SC upper parts are coordinates (3.0416, 3.4965) and (7.1943, 3.6818). SC lower parts are coordinates (6.3707, 0.6637) and (2.8478, 2.4522).

So this both SC spatial arrangement obtained MF SAS synthesis results different from SC spatial arrangement obtained intuitively which shows in Fig. 1.

In Fig. 5 are shown the isolines of the resultant magnetic flux density with SAS is on.

As can be seen from this Fig. 5, minimum magnetic flux density value in the shielding space is 0.2 μT. Initial magnetic flux density value generated by OPL in the shielding space is 0.75 μT. Therefore, the SAS shielding factor maximum is more than 3.75 when the active shielding system is on, as can be seen from Fig. 3, magnetic flux density level in all shielding space does not exceed 0.3 μT.

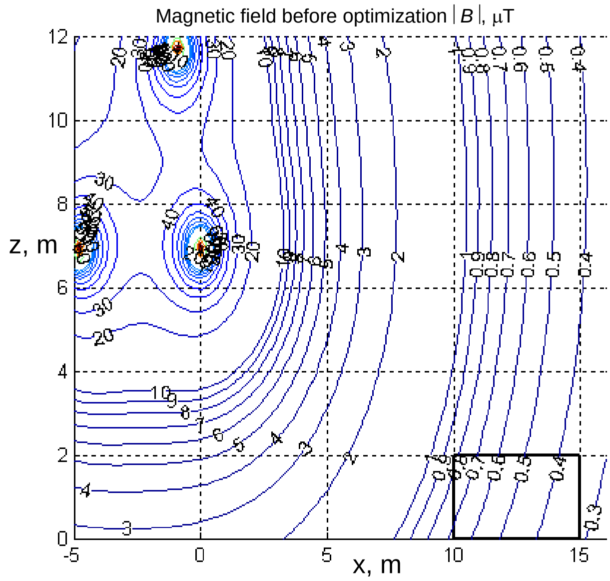

Fig. 4. Isolines of initial magnetic flux density generated by overhead power lines with phase conductors triangular arrangements

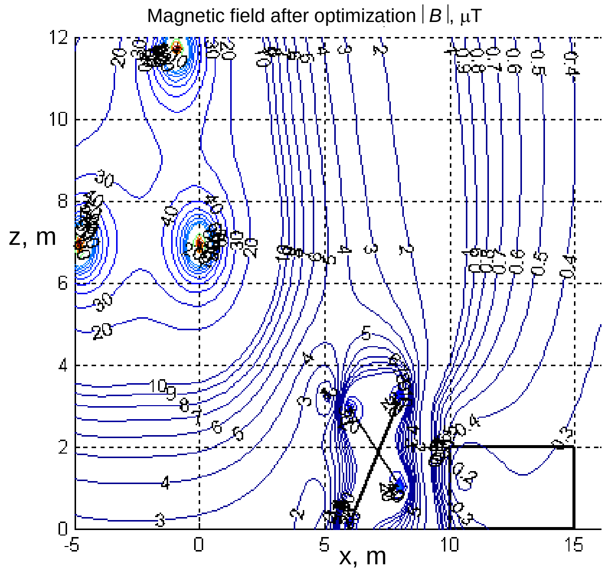

Fig. 5. Isolines of the resultant magnetic flux density with the system of active shielding is on

In Fig. 6 are shown the MF STC, generated by OPL (1); both SC (2) and total MF with SAS is on (3).

The STC of initial MF generated by OPL with phase conductors triangular arrangements close to the circle. STCof MF generated by both SC is also close to the circle of the STC of initial MF, which ensures high shielding factor.

However, STC of MF generated separately by only single first SC or only single second SC are straight lines. In Fig. 7 are shown comparison between MF STC generated separately by only single first SC (1) and only single second SC (2).

Naturally, the STC of the resulting MF generated by OPL and only single SC is an ellipse, which will be shielded by another SC. In Fig. 8 are shown the STC of the initial MF generated by OPL, shielding MF generated by only single first SC and the resulting MF when only single first SC is used.

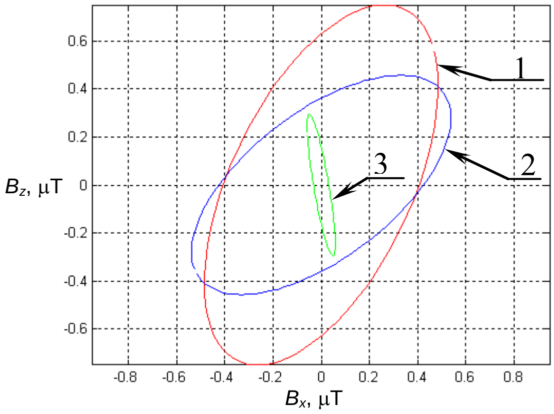

Fig. 6. Comparison of space-time characteristics of magnetic flux density between with and without system of active shielding and shielding coils

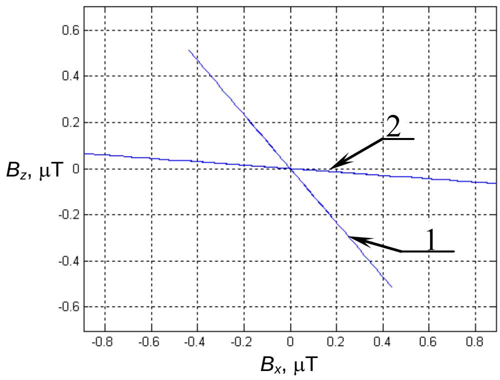

Fig. 7. Comparison between space-time characteristics of magnetic flux density generated separately by only single first (1) and by only single second (2) shielding coils

As can seen from Fig. 8, the STC of the resulting MF is a strongly elongated ellipse, the semi-major axis of which is almost two times larger than the STC of the initial MF, and therefore, due to only single first SC work, initial MF is almost twice re compensated. However, then after second SC switching resulting MF STC becomes significantly less than the STC of initial MF, which ensures high shielding factor. Note that the STC of the resulting MF, left after the operation of only single first SC, practically parallel with the STC generated by the MF using only single second SC.

In Fig. 9 are shown the STC of the initial MF generated by OPL, shielding MF generated by only single second SC and the resulting MF when only single second SC is used.

Experimental research. Consider the experimental research of SAS model with two SC. Figure 10 shows picture of such two SC spatial arrangement. SC upper parts of SC located at heights of 3.5 m and 3.7 m from the ground, and the SC lower parts located at heights of 0.66 m and 2.5 m from the ground.

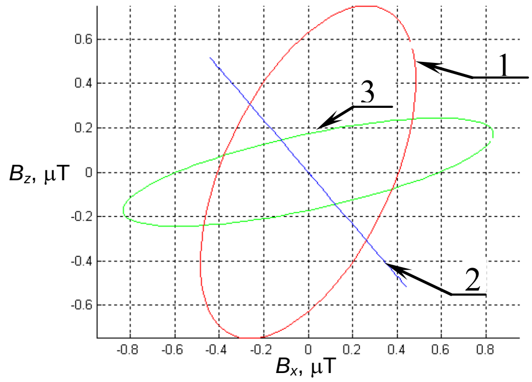

Fig. 8. Comparison between space-time characteristics of magnetic flux density without and with system of active shielding with only single first shielding coil and only single first shielding coil

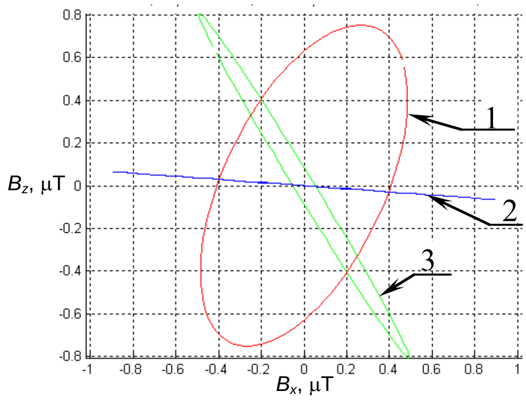

Fig. 9. Comparison between space-time characteristics of magnetic flux density without and with system of active shielding with only single second shielding coil and only single second shielding coil

Fig. 10. Picture of both shielding coil spatial arrangement of system of active shielding model

An important issue when setting up the two degree of freedom robust SAS is determining of spatial arrangement location points and spatial orientation of the MF sensors. For implementing of two degree of freedom robust SAS, two MF sensors must be placed in shielding space point with coordinates (10.6, 1.25), at which the calculated magnetic flux density value takes a minimum value. The MF both sensors axis must be parallel to the appropriate both SC MF STC lines. With this spatial orientation, both MF sensors measure the total MF generated by power lines and appropriate only single first

SC and only single second SC. In Fig. 11 are shown both MF sensors spatial arrangement in shielding space point for closed loop control by two degree of freedom robust SAS model.

Fig. 11. Picture of both magnetic field sensors spatial arrangement in shielding space point for closed loop control by system of active shielding model

For implementing of feed forward regulator for open loop control by two degree of freedom robust SAS, only single MF sensors must be placed outside shielding space point. In Fig. 12 is shown picture of such MF sensor spatial arrangement outside the shielding space for open loop control by SAS model.

Fig. 12. Picture of magnetic field sensor spatial arrangement outside the shielding space for open loop control by system of active shielding model

Both SC of the SAS model are square shape, contains 20 winds and powered by amplifiers TDA7294. The SAS contains an external magnetic flux density controller and an internal current controller. An inductive sensor used as an magnetic flux density sensor, and the magnetic flux density measurement is performed by magnetometer type EMF-828 of the firm LUTRON. In Fig. 13 are shown picture of system of active shielding model. SAS powered by autonomous generator. In Fig. 14 is shown picture of such autonomous generator.

In Fig. 15 are shown experimental isolines of the resultant magnetic flux density with SAS with only single first SC is on. In Fig. 16 are shown experimental isolines of the resultant magnetic flux density with SAS with only single second SC is on. Note that in spite of that MF STC with only the first and only the second SC is on are very different, as are shown in Fig. 8 and Fig. 9. But experimental isolines of the resultant magnetic flux density with only first and only second SC are very different, as are shown in Fig. 15 and Fig. 16 differ slightly.

Fig. 13. Picture of system of active shielding model

Fig. 14. Picture of autonomous generator powered by system of active shielding model

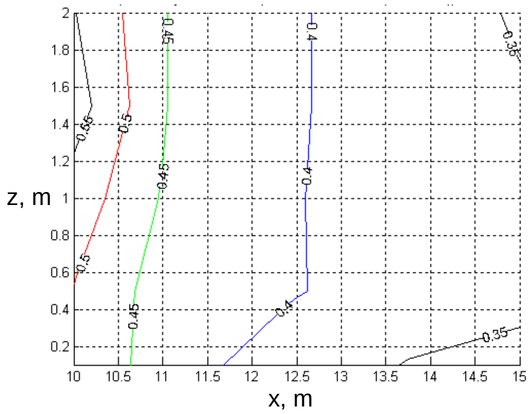

Fig. 15 Experimental isolines of the resultant magnetic flux density with SAS with only single first shielding coil is on

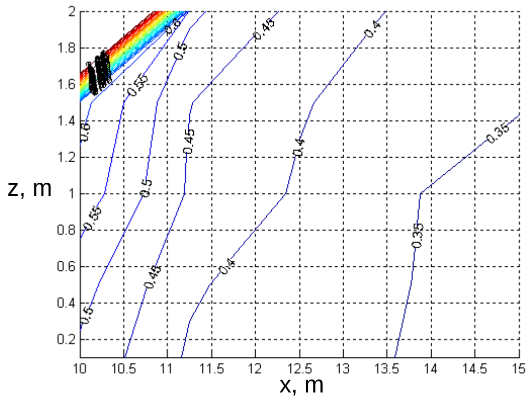

Fig. 16. Experimental isolines of the resultant magnetic flux density with SAS with only single second shielding coil is on

In Fig. 17 are shown comparison between magnetic flux density measurements and simulations with and without

SAS. Comparison between experimental and calculated results of magnetic flux density values in shielding zone shows that their spread does not exceed 20 %. The experimental shielding factor of SAS is also more than 2.5 units.

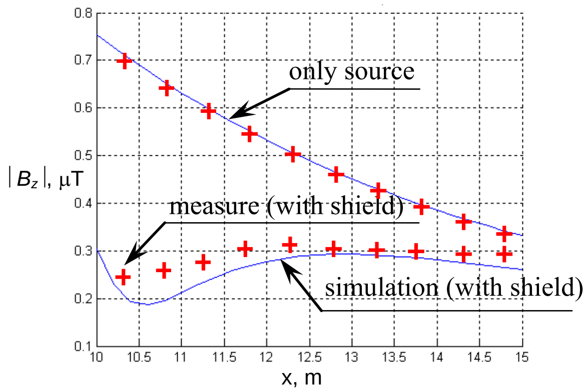

Fig. 17. Comparison of magnetic flux density between measurements and simulations with and without system of active shielding

Actually, the single-circuit 110 kV OPL with phase conductors triangular arrangements current are 200-500 *A*. SAS synthesis, computer simulation and field experimental given for OPL 250 *A* current. At this OPL current magnetic flux density level in all shielding space does not exceed 0.3 μT. Therefore such SAS provides Ukraine sanitary standards level 0.5 μT for OPL current up to 416 A. At this OPL current initial magnetic flux density level in shielding space is 1.25 μT, which is 2.5 times higher than Ukraine sanitary norms.

Conclusions.

1. For the first time the synthesis and field experimental research of two degree of freedom robust two-circuit system of active shielding of magnetic field with circular space-time characteristic, generated by overhead power lines with «triangle» type of phase conductors arrangements for reducing the initial magnetic flux density up to the sanitary standards level and reducing the sensitivity of the system to plant parameters uncertainty are given.
2. The synthesis is based on multi-criteria stochastic game decision, which is based on multiswarm stochastic multi-agent optimization from Pareto-optimal solutions. As a result the spatial position of two shielding coils and the parameters of the regulator are determined.
3. System reduce the the magnetic flux density in shielding space more than 2.5 times and has less to 20 % sensitivity to plant parameters uncertainty in comparison with the known systems.
4. Based on field experimental research of two degree of freedom robust two-circuit system of active shielding are shown that experimental and calculated magnetic flux density values in the shielding space spread does not exceed 20 %.

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