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Method of adjustment of three circuit system of active shielding of magnetic field in multi-storey buildings from overhead power lines with wires triangular arrangement

Aim. *For the first time the method of adjustment of three circuit system of the active shielding of the magnetic field based on experimentally determined space-time characteristics to increase the shielding factor in a multi-storey building located near a single-circuit overhead transmission lines with a wires triangular arrangement was developed.* ***Methodology****. When synthesizing the laboratory model of system of active shielding the coordinates of spatial arrangement and of three shielding coils, the currents in shielding coils and resulting magnetic flux density value in the shielding space were calculated. The synthesis is based on the multi-criteria game decision, in which the payoff vector is calculated on the basis on quasi-stationary approximation solutions of the Maxwell equations. The game decision is calculated based on the stochastic particles multi swarm optimization algorithms.* ***Results****. Computer simulation and experimental research of the space-time characteristics of laboratory model of three circuit system of active shielding of magnetic field, generated by overhead power lines with phase conductors triangle arrangements in multi-storey building are given. The possibility of initial magnetic flux density level reducing to the sanitary standards level is shown.* ***Originality****. For the first time the synthesis and adjustment of laboratory model of three circuit system of active shielding of magnetic field based on experimentally determined space-time characteristics to increase the shielding factor in a multi-storey building located near a single-circuit overhead transmission lines with a wires triangular arrangement carried out.* ***Practical value****. Practical recommendations from the point of view of the implementation of developed method of adjustment of the three circuit system of the active shielding of the magnetic field based on experimentally determined space-time characteristics in a multi-storey building located near a single-circuit overhead transmission lines with a triangular arrangement of wires are given.* References 48, figures 11.

Key words: **overhead power lines, magnetic field, space-time characteristics, system of active shielding, shielding factor, computer simulation, experimental research.**

Мета. *Вперше розроблено метод налаштовування триконтурної системи активного екранування магнітного поля на основі експериментально визначених просторово-часових характеристик для коефіцієнту екранування в багатоповерховому будинку, розташованому поблизу одноколових повітряних ліній електропередачі з трикутним розташуванням проводів.* ***Методологія****. При синтезі лабораторної моделі системи активного екранування були розраховані координати просторового розташування трьох екрануючих обмоток, струми в екрануючих обмотках та результуюче значення індукції магнітного поля в просторі екранування. Синтез системи базується на рішенні багатокритеріальної гри, в якій вектор виграшу розраховується на основі квазістаціонарних апроксимаційних розв'язків рівнянь Максвелла. Рішення гри розраховується на основі алгоритмів стохастичної оптимізації мультироєм частинок.* ***Результати****. Наведено результати комп'ютерного моделювання та експериментальних досліджень просторово-часових характеристик лабораторної моделі триконтурної системи активного екранування магнітного поля, яке створюється повітряними лініями електропередачі з трикутним розташуванням фазних провідників у багатоповерховому будинку. Показано можливість зниження початкового рівня індукції магнітного поля до санітарних норм.* ***Оригінальність****. Вперше проведено синтез та налаштовування лабораторної моделі триконтурної системи активного екранування магнітного поля на основі експериментально визначених просторово-часових характеристик для підвищення фактору екранування провідників у багатоповерховому будинку, розташованому поблизу одноколових повітряних ліній електропередачі з трикутним розташуванням проводів.* ***Практична цінність****. Наведено практичні рекомендації з точки зору реалізації розробленого методу налаштовування триконтурної системи активного екранування магнітного поля на основі експериментально визначених просторово-часових характеристик в багатоповерховому будинку, який розташовано поблизу одноконтурних повітряних ліній електропередачі з трикутним розташуванням проводів.* Бібл. 48, рис. 11.

Ключові слова: **повітряні лінії електропередачі, магнітне поле, просторово-часові характеристики, система активного екранування, коефіцієнт екранування, комп'ютерне моделювання, експериментальні дослідження.**

Introduction. Most of the existing 10-330 kV overhead transmission lines, which were built during the last 50 years, often pass near old residential buildings. These overhead transmission lines generate a magnetic field of power frequency inside residential buildings, the level of which exceeds the sanitary standards of Ukraine [1]. One of the most economically feasible approach to the further safe operation of these residential buildings is to reduce the level of magnetic field (MF) inside these buildings by means of active shielding [2–4]. In Ukraine, in the area of old residential buildings, 110 kV power transmission lines with a triangular suspension of wires are the most common.

Such overhead transmission lines generate magnetic field with a circular space-time characteristic. To compensate for such a magnetic field, at least two compensation windings are needed even when shielding magnetic field inside one-story residential buildings. When shielding such a magnetic field in multi-storey buildings, three or more compensation windings may be required [5–7]. The adjustment of such a three circuit system is a rather complex scientific problem. The problem of adjustment of three circuit system of the active shielding consists in experimentally adjustment of parameters of current regulators in compensation windings. For each compensation winding, it is necessary to determine the magnitude of the gain and phase shift for the regulator, which operates according to the open-loop control principle. And at the same time for each compensation winding, it is necessary to determine the magnitude of the gain for the regulator, which operates according to the closed-loop control principle with feedback on the induction of the resultant magnetic field.

A feature of the system of the active shielding under consideration is the highly elongated space-time characteristic ellipses of the resulting MF during the operation of individual compensating windings [8–10]. Moreover, when the windings work together, the magnetic field generated by the individual windings is mutually compensated, which makes it possible to obtain a high compensation efficiency of the initial magnetic field [11, 12]. Therefore, when adjustment the system of the active shielding, it is necessary to use space-time characteristic and therefore the development of method of adjustment of three system of the active shielding of the magnetic field based on experimentally measured space-time characteristics is important and urgent scientific problem.

The aim of the work is to develop of method of adjustment of three circuit system of the active shielding of the magnetic field based on experimentally determined space-time characteristics to increase the shielding factor in a multi-storey building located near a single-circuit overhead transmission lines with wires triangular arrangement.

Statement of the research problem. The State Institution “Institute of Technical Problems of Magnetism of the NAS of Ukraine” developed the laboratory model of a single-circuit overhead power transmission line with a triangular arrangement of wires on a scale of 1 to 15. Figure 1 shows such a laboratory model.

Fig.1. The laboratory model of a single-circuit overhead power transmission line with a triangular arrangement of wires

Consider the synthesis and adjustment of the system of the active shielding of the space-time characteristic generated by this model of the power transmission line in the model of a multi-storey building, as it is shown in Fig. 2.

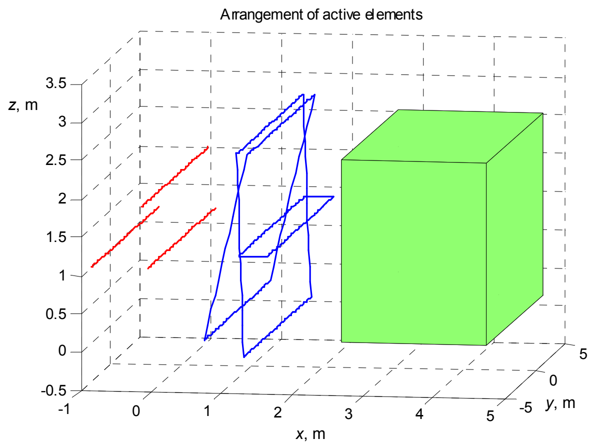


Fig. 2. The location of model of overhead power line, and shielding space in model of multi-storey building

Let us introduce a vector of unknown parameters of the system of active shielding, the components of which are the coordinates of shielding coils and parameters of the regulator [13–18] and vector of uncertainty parameters of initial magnetic field model [19–23]. Then calculate of vector of unknown parameters of system of active shielding and of vector of uncertainty parameters in the form of a solution of multi-criteria game. The components vector payoff in this game are levels of magnetic flux density at points of the shielding space. These components are nonlinear functions of the vectors of unknown parameters and uncertainty parameters and are calculated on basis of Maxwell equations quasi-stationary approximation solutions [24–28]. First player is vector of unknown parameters and its strategy is minimization of vector payoff. Second player is vector of uncertainty parameters and this strategy is maximization of the same vector payoff [29–33].

And therefore the solution of multi-criteria game is calculated from the condition of minimum value of vector payoff for the vector of unknown parameters but the maximum value of vector payoff for the vector uncertainty parameters. This technique corresponds to the standard worst-case robust systems synthesis approach [34–38].

To find multi-criteria game solution from Pareto-optimal set solutions taking into account binary preference relations [39, 40] used particle multi swarm optimization algorithm [41–47], in which swarms number equal number of vector payoff components.

Computer simulation results. Consider the result of synthesis of model of system of the active shielding of magnetic field with circular space-time characteristic created by three-phase single-circuit overhead power line 110 kV with phase conductors triangular arrangements in a multi-storey building, as it is shown in Fig. 2. In order to reduce the level of magnetic flux density of the initial magnetic field throughout the entire multi-storey building to the level of sanitary standards of Ukraine, in this case, it is necessary to use three shielding windings, as it is shown in Fig. 2.

Figure 3 shows lines of equal level of module of the resultant magnetic flux density when the system of active shielding is on.

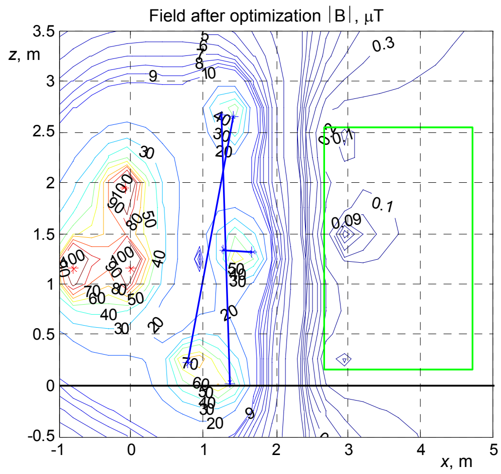


Fig. 3. Isolines of the resultant magnetic flux density when the system of active shielding is on

As follows from this figure, the level of magnetic flux density of the resulting magnetic field in the entire space of a multi-storey building does not exceed the level of 0.5 μT, which corresponds to the sanitary standards of Ukraine. Note that in the center of the multi-storey building under consideration, the level of magnetic flux density of the resulting magnetic field does not exceed 0.2 μT, and, therefore, in this part of the space, using an system of active shielding, the induction level of magnetic flux density of the initial magnetic field can be reduced by more than 20 times.

Figure 4 shows the space-time characteristics of the magnetic flux density vector of magnetic field generated by: 1) overhead power line; 2) all three shielding coils and 3) the resultant magnetic field when the all three shielding coils are on.

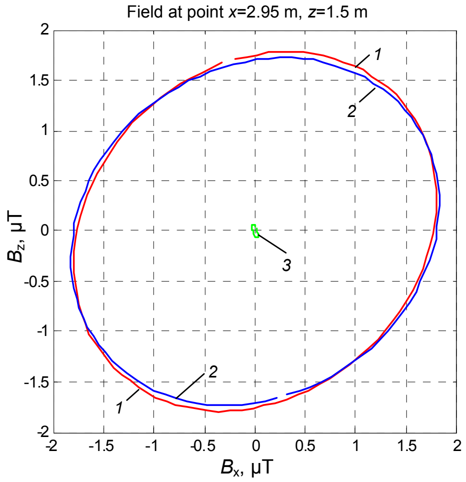


Fig. 4. Space-time characteristics of magnetic flux density without and with system of active shielding with all three shielding coils and only all three shielding coils

Now let us consider the shielding efficiency of the original magnetic field when only one single firs shielding coil is used at optimal values of the regulator of this coil. Figure 5 shows the space-time characteristics of the magnetic flux density vector of magnetic field generated by: 1) overhead power line; 2) the only one single first shielding coil and 3) the resultant magnetic field when the only one single first shielding coil is on.

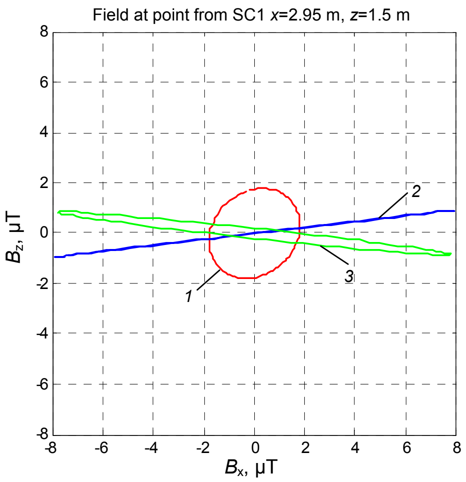


Fig. 5. Space-time characteristics of magnetic flux density without and with system of active shielding with only one single first shielding coil (SC1)

Now let us consider the shielding efficiency of the original magnetic field when only one single second shielding coil is used at optimal values of the regulator of this coil. Figure 6 shows the space-time characteristics of the magnetic flux density vector of magnetic field generated by: 1) overhead power line; 2) the only one single second shielding coil and 3) the resultant magnetic field when the only one single second shielding coil is on.

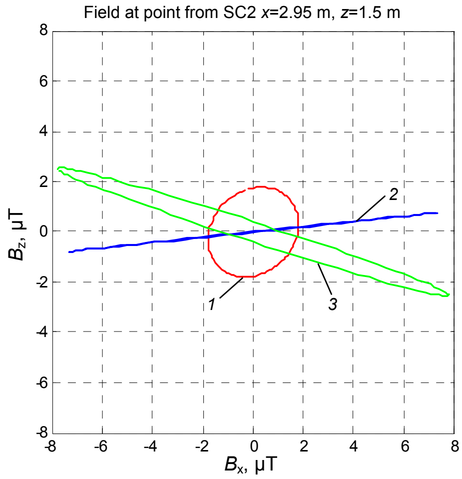


Fig. 6. Space-time characteristics of magnetic flux density without and with system of active shielding with only one single second shielding coil (SC2)

Now let us consider the shielding efficiency of the original magnetic field when only one single third shielding coil is used at optimal values of the regulator of this coil. Figure 7 shows the space-time characteristics of the magnetic flux density vector of magnetic field generated by: 1) overhead power line; 2) the only one single third shielding coil and 3) the resultant magnetic field when the only one single third shielding coil is on.

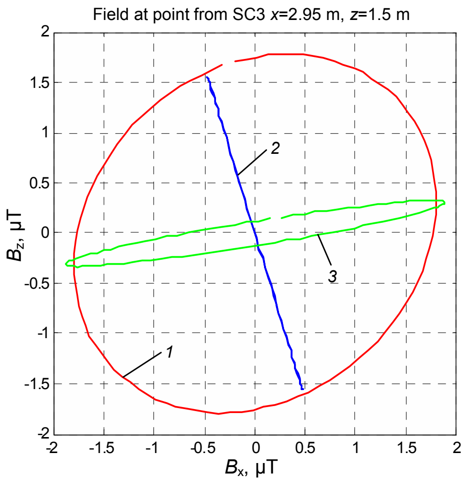


Fig. 7. Space-time characteristics of magnetic flux density without and with system of active shielding with only one single third shielding coil (SC3)

Now let us consider the shielding efficiency of the original magnetic field when only both first and second shielding coils are used at optimal values of the regulator of these coils. Figure 8 shows the space-time characteristics of the magnetic flux density vector of magnetic field generated by: 1) overhead power line; 2) only both first and second shielding coils and 3) the resultant magnetic field when the only both first and second shielding coils are on.

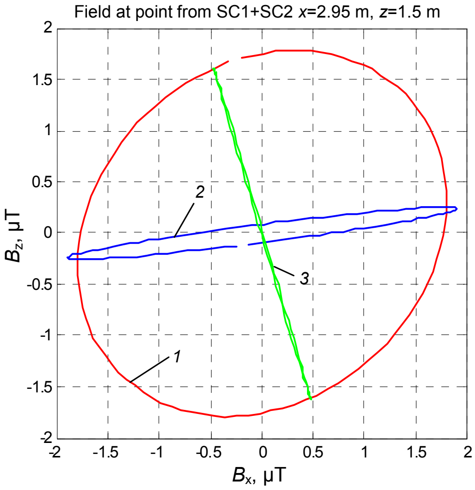


Fig. 8. Space-time characteristics of magnetic flux density without and with system of active shielding with only both first and second shielding coils and only both first and second shielding coils

Note that from a comparison of the space-time characteristics shown in Fig. 8 follows that the space-time characteristic of the resulting magnetic field remaining after the operation of the only first and second shielding coil is a highly elongated ellipse, the major axis of which practically coincides with the space-time characteristics of the magnetic field generated by only one third shielding coil, as it shown in Fig. 7.

As a result, with the help of the third shielding coil, the major axis of the space-time characteristic of the resulting magnetic field, which remains after the operation of the only first and second shielding coils, is compensated effectively. Due to such compensation, a sufficiently high shielding factor of 20 is provided in the system with the simultaneous operation of all three shielding coils.

Note that the calculated space-time characteristic for the laboratory model of a single-circuit overhead power transmission line with a triangular arrangement of wires shown in Fig. 3–7 differs from the corresponding space-time characteristic, calculated in [48] for a five-storey building.

Results of adjustment of system of the active shielding. Based on the system of the active shielding obtained as a result of the synthesis, the coordinates of the location of the compensation windings relative to the overhead transmission lines were calculated. According to the coordinates obtained, the installation of three compensation windings relative to the wires of the power transmission line was carried out.

A feature of the system under consideration is the fact that when compensating the initial magnetic field with the help of separate compensation windings, the space-time characteristic of the resulting space-time characteristic has the shape of a strongly elongated ellipse. In this case, there is a significant (2–3 times) overcompensation of the initial magnetic field. Such a magnetic field must be compensated for with another compensation winding.

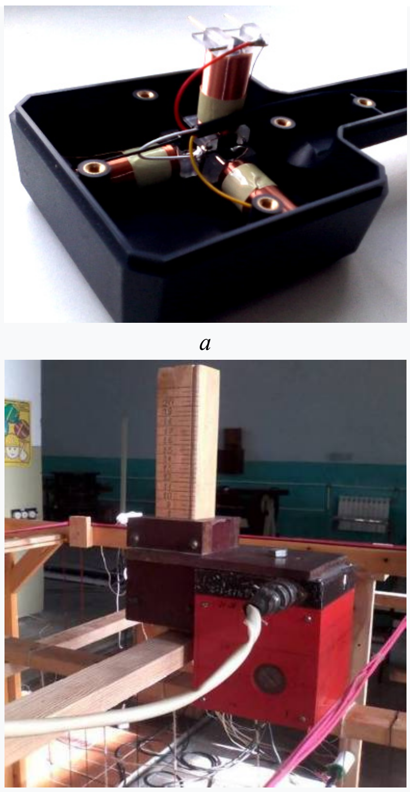
To realize the high shielding efficiency of such a magnetic field, it is necessary that the space-time characteristic magnetic field generated by the compensation winding be strictly parallel to the space-time characteristic of the original magnetic field.

Therefore, to adjustment of such system of the active shielding, it is necessary to use space-time characteristic.

The simplest way is to calculate the magnetic induction of an infinitely long wire without taking into account its sagging. In this case, we can restrict ourselves to a two-dimensional model of the magnetic field, since the component of the magnetic induction vector, located parallel to this wire, is equal to zero. Taking into account the wire sag and the complex configuration of the wires, a three-dimensional model of the magnetic field is used with a significantly large number of elementary sections.

Naturally, to synthesize the initial exact model of the magnetic field, initial data are required for the spatial location of all conductors of the group of all power lines, relative to the space under consideration, as well as the values of the currents and phases of all conductors of all power lines. For this purpose, measurements were carried out, experimental studies of the geometric dimensions of all power lines and the values of the vectors of the magnetic field induction at various points in space.

Space-time characteristic of a three-dimensional space-time characteristic is a surface formed by the end of the magnetic field induction vector with time change. To measure the instantaneous value of the induction vector of such a space-time characteristic, it is necessary to have three measuring coils, the axes of which are orthogonal to each other. Figure 9,*a* shows such three coils for measuring system (Fig. 9,*b*) of three components of space-time characteristic.



a

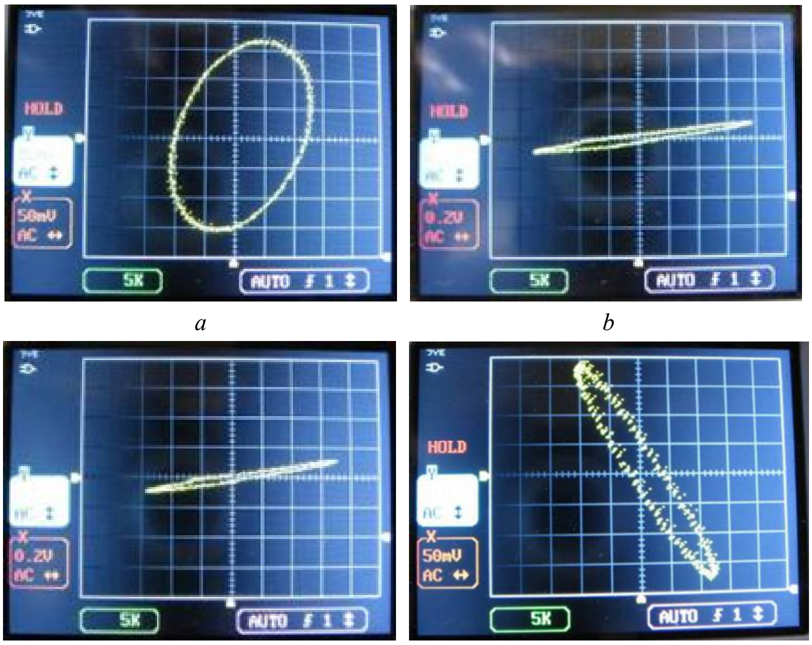
b

Fig. 9. The measuring windings (*a*) of system for measuring space-time characteristic (*b*)

For sufficiently long transmission lines of the magnetic field component, the parallel line of wires is practically zero. Therefore, the mathematical model of a space-time characteristic power transmission line is often adopted in the form of a two-dimensional model. For such a model, the space-time characteristic is a flat figure.

A special measuring system has been developed for measuring space-time characteristic. This measuring system contains two measuring coils of magnetic field induction the axes of which are orthogonal to each other and directed along the axes of the original magnetic field. Figure 9,*b* shows such measuring system.

When setting up this space-time characteristic measurement system, it is important to ensure the identity of the channels for measuring the amplitude and phase of the induction of the original magnetic field.



a *b* *c* *d*

Figure 10,*a* shows space-time characteristic initial of magnetic flux density of laboratory model of overhead power line. Let us now consider the experimental space-time characteristic magnetic field generated by laboratory model of overhead power line and compensating windings during their autonomous operation.

Figures 10,*b–d* show space-time characteristic of three compensating windings during their autonomous operation. As you can see from this figure, the space-time characteristics of the first and second windings practically coincide.

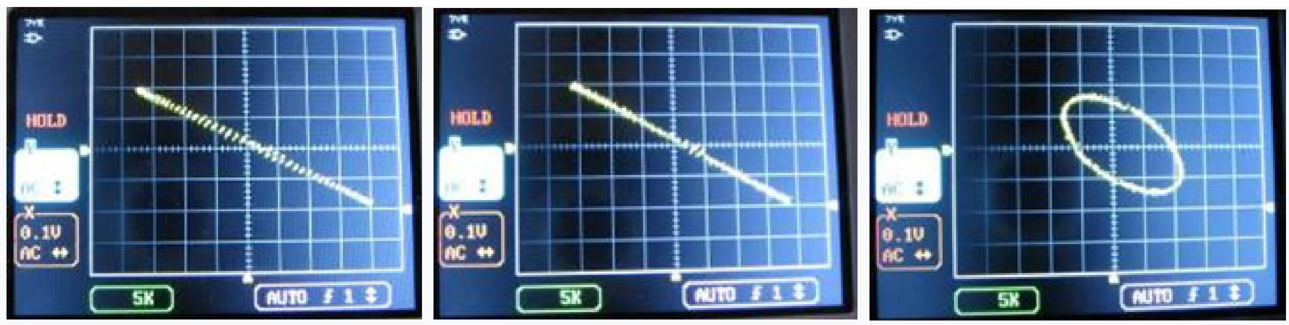
Fig. 10. Experimentally measured space-time characteristics of initial magnetic flux density of laboratory model of overhead power line and shielding coils during their autonomous work

Let us consider the experimentally measured space-time characteristics of resultant magnetic flux density of laboratory model of overhead transmission lines and shielding coils during their simultaneous work.

Figure 11,*a* shows space-time characteristic of resultant magnetic flux density of laboratory model of overhead transmission lines and first shielding coils during their simultaneous work.

Figure 11,*b* shows space-time characteristic resultant magnetic flux density of laboratory model of overhead transmission lines and second shielding coils during their simultaneous work. As you can see from this figure, these space-time characteristic are practically coincide.

Let us now consider the space-time characteristic resulting magnetic field with the simultaneous operation overhead transmission lines, first and second windings. Figure 11,*c* shows the space-time characteristic of such an magnetic field. As can be seen from this figure, when the first and second windings work together, the horizontal components of the magnetic field generated by the first and second windings during their individual operation are practically compensated.



a *b* *c*

Fig. 11. Experimentally measured space-time characteristics of resultant magnetic flux density of laboratory model of overhead transmission lines and shielding coils during their simultaneous work

The space-time characteristic of the resulting magnetic field, which remained after the joint operation of the first and second compensating windings, is practically parallel to the space-time characteristic of the MF generated by the third winding during its separate operation, as shown in Fig. 10,*d*, 11,*c*.

With the simultaneous operation of the first and second windings, the third winding is adjusted in such a way that, due to its operation, the magnetic flux density of the magnetic field remaining after the joint operation of the first and second windings is compensated. This allows makes it possible to effectively compensate the resulting magnetic field remaining from the simultaneous operation of the first and second compensating windings, and as a result – effectively compensate for the original magnetic field generated by the power transmission line.

The experimentally measured space-time characteristic of the resulting magnetic field, remaining after the simultaneous operation of all three compensating windings, is practically a point. The induction level of the resulting magnetic field measured by the magnetometer is 0.5 μT. Thus with the help of the developed method of adjustment of a three circuit system of the active shielding the level of magnetic flux density of the magnetic field generated in a multi-storey building by a overhead transmission lines with a triangular arrangement of wires based on experimentally measured space-time characteristics the shielding factor of initial magnetic field is increased by more than 8 times.

Note that the calculated value of the shielding factor in a small zone of the shielding space is more than 20 units, as follows from Fig. 3. However, the experimental value of the screening factor in the same small zone of the screening space does not exceed 8 units. This is due to the presence of noise in the magnetic field induction sensors.

Conclusions.

1. For the first time the method of adjustment of three circuit system of the active shielding of the magnetic field based on experimentally determined space-time characteristics allowing to significantly increase the shielding factor of the magnetic field in a multi-storey building located near a single-circuit overhead transmission lines with wires triangular arrangement was developed.

2. The possibility of increasing the shielding factor to 8 units of the magnetic field by the active shielding system in a multi-storey building located near an overhead power line with wires triangular arrangement by using the developed method of adjustment is theoretically substantiated and experimentally confirmed.

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

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