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MITIGATION OF OVERHEAD LINE MAGNETIC FIELD BY GRID SHIELD WITH ELECTRICALLY SEPARATED SECTIONS

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The paper deals with the mitigation of the overhead line magnetic field by a U-shaped grid shield. We consider grid shields made of conductors, which are grouped into electrically separated sections. Conductors within each section are connected in parallel. We vary the number of sections and their topology. Also we vary the parameters of arms of the U-shaped grid shield, namely the length and the number of conductors. We show that the U-shaped grid shield with two electrically separated sections is advisable to use. The one section consists of conductors of a U-shaped shield stem. Another section consists of conductors of both arms connected in parallel. Also we show that the number of conductors in the arm can be reduced to five, if the quantity of metal of the arm is kept. References 10, figures 3, table 1.
Keywords: overhead line, magnetic field, shielding, reference level.

Introduction. The 10-330 kV overhead lines cross urban areas in Ukraine. They were built over the last 50 years without taking into account modern reference levels for the magnetic field. In the past decade the energy industry of Ukraine has received the reference level in 0.5 μT for living spaces [1]. The overhead line magnetic field depends on a current load, an arrangement of conductors, and a distance to a building. Nevertheless the magnetic field often exceeds the reference level inside buildings closed to overhead lines. As the magnetic field penetrates inside with almost no attenuation [2], some measures to reduce it are to be taken.

The overhead line reconstruction is the most efficient method to reduce the magnetic field. The one way is to move the overhead line away from residential buildings. Another way is to replace it by the underground cable line. However the reconstruction needs significant capital expenditures, which limits its practical application. So the shielding of the overhead line magnetic field is more promising to meet modern reference levels.

In general, different types of shields are used to reduce the power line magnetic field. Each of them has advantages and disadvantages. Active loops provide comparably high shielding efficiency [3]. But they require a source of electrical energy (to generate the current in conductors), detectors, and a control system. Also expenses for maintenance checkup are relatively high. Passive loops are free of these disadvantages, but their shielding efficiency is comparably low [4]. Magnetic shields are made of materials with high permeability. They are used for the cable line magnetic field mitigation, when "shielding of a source" technique is implemented [5]. For "shielding of a subject" technique implementation the electromagnetic shields are used [6]. They are usually made of aluminum due to its relatively high conductivity and low price. Traditionally electromagnetic shields consist of plates making it difficult to install on building walls.

A novel approach to overhead line magnetic field mitigation is proposed in [7]. It is based on the usage of so-called grid shields made of aluminum conductors. Note that similar types of shields are used to develop electric machines with low-level external magnetic field [8]. To increase shielding efficiency on edges of shields, the U-shaped grid shields are proposed in [9]. The recent papers show, that efficiencies of overhead line magnetic field reduction by the grid shield and by the electromagnetic shield are similar, if their shapes and quantities of metal are the same. Compared to traditional electromagnetic shields, the grid shields are more ergonomic because of their transparency to natural light. The disadvantage of known grid shields is the necessity to connect all its conductors in parallel.

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The **goal** of this paper is to simplify the grid shield topology while maintaining the shielding efficiency of the overhead line magnetic field.

Prototype of shield. The study is based on the assumption that infinitely long conductors of the overhead line are parallel to each other. Parameters of the overhead line and the building are taken from [7, 9]. The coordinates of conductors are $x_1 = x_2 = x_3 = -20$ m, $y_1 = -4$ m, $y_2 = 0$, $y_3 = 4$ m. The ground level corresponds to $y = -20$ m. The overhead line runs at frequency 50 Hz. The RMS current is 1000 A and the initial phases of currents are $\varphi_1 = -2\pi/3$, $\varphi_2 = 0$, $\varphi_3 = 2\pi/3$. We use [2] to calculate the RMS value of the magnetic field B_0 of the overhead line in a free space. Fig. 1 shows the distribution of B_0. The building is marked with smooth and dashed lines. It is 40 m high, 20 m width, and 20 m away from the overhead line. The RMS value B_0 exceeds the reference level 0.5 μT in the whole building.

Based on recent research [7, 9] we choose the following U-shaped grid shield as the prototype. The prototype is made of 121 conductors parallel to each other and to the overhead line. All conductors are connected in parallel. The diameter of each conductor is 8 mm. The distance between adjacent conductors is equal to 0.5 m. The U-shaped smooth line in Fig. 1 shows the arrangement of cross-sections of conductors.

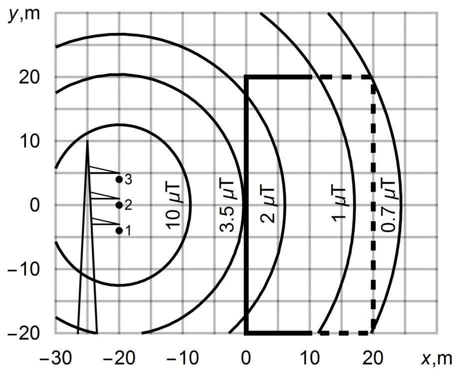


Fig. 1

The prototype has two arms 10 m long. Cross-sections of 21 conductors are arranged along each of arms. Their coordinates are $x_k = (0.5 \cdot k)\,\text{m}$, $y_k = \pm 20\,\text{m}$, where counter k goes from 0 to 20. Cross-sections of remaining conductors are arranged along the vertical 40 m high. This part of the shield we call the stem. Their coordinates are $x_k = 0$, $y_k = (-20 + 0.5 \cdot k)\,\text{m}$, where counter k goes from 1 to 79.

We use a model developed in [7] to calculate the magnetic field shielded by the prototype. We modify the model assuming the current density being uniform in each overhead line conductor. So an equation for the phasor of the magnetic vector potential $\dot{A}$ has the following form:

$$\frac{\partial^2 \dot{A}}{\partial x^2} + \frac{\partial^2 \dot{A}}{\partial y^2} - j\mu_0\omega\sigma\dot{A} + \mu_0\dot{\delta} = 0, \tag{1}$$

where j is an imaginary unit; $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the vacuum permeability; $\omega = 2\pi \cdot 50$ rad/s is the angular frequency; $\sigma = 3.5 \cdot 10^7$ S/m is the conductivity of aluminum, and σ goes to zero for the non-conductive ambient; $\dot{\delta}$ is a density current phasor for overhead line conductors, and it goes to zero for the non-conductive ambient and conductors of the shield.

The density current phasor $\dot{\delta}$ is defined as the ratio of current phasor of the overhead line conductor to its cross-section S_k. So

$$\dot{\delta}_k = 1000\sqrt{2} \cdot e^{j\varphi_k} / S_k, \tag{2}$$

where subscript k goes from 1 to 3.

The boundary conditions between conductive domains (conductors of the overhead line and the shield) and the non-conductive ambient are the following:

$$\begin{cases} \dot{A}_i = \dot{A}_e, \\ \partial\dot{A}_i / \partial n = \partial\dot{A}_e / \partial n, \end{cases} \tag{3}$$

where subscripts i and e indicate the location of the observation point (x, y) inside and outside conductive domains respectively, and n is the unit vector normal to the boundary surface.

We carry out the numerical simulation with the software package *COMSOL Multiphysics*. Fig. 2, *a* shows the distribution of the magnetic field shielded by the prototype made of 121 conductors. The profile of the prototype is shown schematically with markers. The magnetic field exceeds the reference level only in relatively small corner areas. We use $\eta = S / S_0 \cdot 100\%$ as a quantitative assessment of shielding efficiency, where S_0 is the total shielding area, and S includes subareas that meet the reference levels for the magnetic field. According to [1] we take into account only areas distant more than 0.5 m from building walls. Then S_0 is the product of 39 m and 19 m. The analyze of Fig. 2, *a* gives S=734 m^2. So the shielding efficiency η of the prototype is equal to 99.1%.

Shields with electrically separated sections. The idea of the simplification of the grid shield topology is to use electrically separated sections. Conductors within the section are connected in parallel, and there is no electrical connection between separated sections. We consider three types of grid shields with electrically separated sections. Every shield shown in Fig. 2 has 121 conductors. The diameter of every conductor is 8 mm. The arrangement of conductors is the same and the distance between adjacent conductors is 0.5 m. Profiles of shields are shown schematically with markers. Electrically separated sections have different markers.

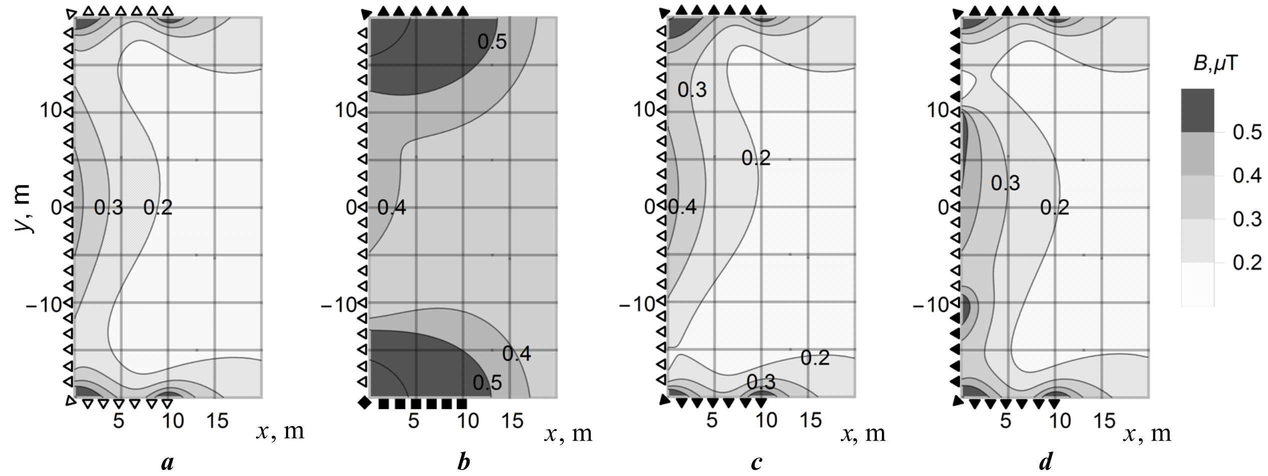


Fig. 2

To simplify the prototype, we divide it into three electrically separated sections shown in Fig. 2, *b*. So conductors are connected in parallel within the stem and within each of arms. To calculate the magnetic field distribution, we add *extra conditions* to the system (1)-(3), namely the total current within every section in equal to zero. Fig. 2, *b* shows that the magnetic field exceeds the reference level in corner areas. The shielding efficiency η of the grid shield with three sections is 78.9 %. We associate the relatively low shielding efficiency with the following. The magnetic field of the overhead line with plane (horizontal or vertical) arrangement of conductors is the superposition of α- and β-components [10]. The α-component of the magnetic field decreases faster when moving away from the overhead line. So the overhead line magnetic field approximates its β-component inside the building. The β-component of the magnetic field is created by the loop current in extreme conductors of the overhead line. As the grid shield with three sections does not provide the closed pass for "opposite" eddy currents, the shielding efficiency is low.

To produce the extra closed pass for eddy currents and to increase the shielding efficiency, we connect arms in parallel. In other words, we divide the prototype into two electrically separated sections shown in Fig. 2, *c*. The comparison with Fig. 2, *b* shows the significant decrease of areas where magnetic field exceeds the reference level. The efficiency η of the grid shield with two sections is 98.8 %. And it is negligibly less than the shielding efficiency of the prototype shown in Fig. 2, *a*.

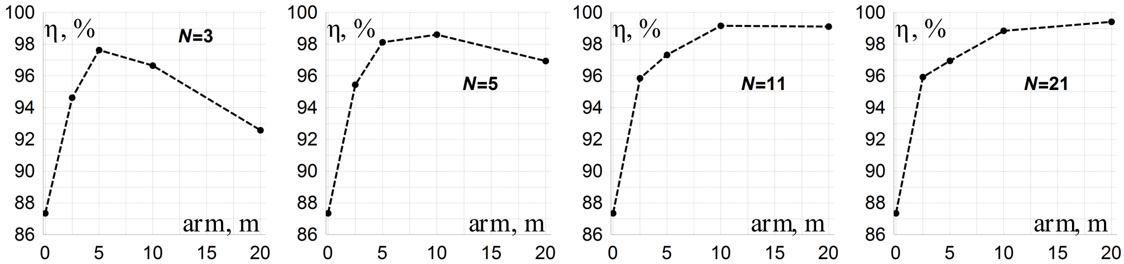
We modify the grid shield with two sections to increase shielding efficiency in corner areas. We connect in parallel the conductors arranged on arms and edges of the stem. The central part of the stem remains electrically separated. The analyze of Fig. 2, *d* gives the shielding efficiency η=98.3 %. Compared to the grid shield with simpler topology shown in Fig. 2, *c*, the shielding efficiency changes insignificantly.

So we conclude that the grid shield with two sections shown in Fig. 2, *c* is the most promising. On the one hand, it is simplified relative to the prototype. On the other hand, the parallel connection of arms allows reducing the β-component of the overhead line magnetic field.

Variation of arm parameters. To simplify the topology of arms, we investigate the dependence of the shielding efficiency η on arm parameters. We vary the number of conductors and the length of the arm while keeping constant its quantity of metal. As the arrangement and the diameter of conductors of the stem are the same, then the quantity of metal of all grid shields under study is constant.

We consider a set of arm topologies. The number of arm conductors N takes values 3, 5, 11 and 21. The arm length takes values 0, 2.5 m, 5 m, 10 m, and 20 m. In the limit case of zero length, the quantity of metal of the arm concentrates in the corner conductor of the grid shield. We carry out numerical simulation and calculate the efficiency η of the grid shield for every arm. Fig. 3 shows the results.

As is expected, the grid shield with no arms has the lowest shielding efficiency η=87.3 %. And it is less than efficiency of the prototype and the grid shield with two sections shown in Fig. 2, *c*. The grid shield with no arms provides inefficient magnetic field mitigation in corner areas despite 36.7 mm diameter of its extreme conductors.



a ***b*** ***c*** ***d***

Fig. 3

The increase of arm length leads to more efficient shielding in corner areas. Accordingly the shielding efficiency η increases. Fig. 3, *a* and *b* show absolute maximums of η for 5 m and 10 m arm, respectively. However the further increase of arm length leads to the shielding efficiency decrease. We associate it with the decreasing of gaps between adjacent arm conductors and the magnetic field penetration through arms. Fig. 3, *c* and *d* do not show absolute maximums because of respectively large number of conductors. We collect best cases for every number of arm conductors *N* in Table 1. The shielding efficiency is the highest when *N* is 11 or 21. But this does not contribute to the topology simplification. So we recommend using 10 m arms length made of 5 conductors. In this case the diameter of arm conductors is 16.4 mm and they are arranged 2.5 m one from another.

N (arm, m)	η, %
3 (5)	97.6
5 (10)	98.6
11 (10)	99.2
21 (20)	99.4

Conclusions. This paper shows that the topology of the U-shaped grid shield can be simplified while maintaining the shielding efficiency of the overhead line magnetic field. The U-shaped grid shield with two electrically separated sections is the most promising. The one section consists of conductors of the stem, and another one consists of conductors of both arms connected in parallel. The shielding efficiency of this shield is negligibly less than the efficiency of the same shield with all conductors connected in parallel. Moreover the arm topology can be simplified, namely the number of conductors in the arm can be reduced to five and the arm length can be reduced to 10 m.

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СНИЖЕНИЕ МАГНИТНОГО ПОЛЯ ВОЗДУШНЫХ ЛИНИЙ ЭЛЕКТРОПЕРЕДАЧИ РЕШЕТЧАТЫМИ ЭКРАНАМИ С ЭЛЕКТРИЧЕСКИ НЕСВЯЗАННЫМИ УЧАСТКАМИ

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Рассмотрено уменьшение магнитного поля воздушной линии электропередачи при помощи U-образного решетчатого экрана, состоящего из нескольких электрически несвязанных секций. При исследовании эффективности U-образных экранов также варьировались длина и число проводов рукавов. Показана целесообразность использования экрана, состоящего из двух электрически несвязанных секций. Одной секцией является перемычка U-образного экрана, другой – рукава экрана, соединенные параллельно. Также показано, что число проводов рукава может быть уменьшено до пяти при условии сохранения его металлоемкости. Библ. 10, рис. 3, табл. 1.

Ключевые слова: линия электропередачи, магнитное поле, экранирование, гранично допустимый уровень.

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ЗМЕНШЕННЯ МАГНІТНОГО ПОЛЯ ПОВІТРЯНИХ ЛІНІЙ ЕЛЕКТРОПЕРЕДАЧІ ҐРАТЧАСТИМИ ЕКРАНАМИ З ЕЛЕКТРИЧНО НЕЗВ’ЯЗАНИМИ ДІЛЯНКАМИ

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Розглянуто зменшення магнітного поля повітряної лінії електропередачі за допомогою U-подібного ґратчастого екрану, що складається з декількох електрично незв’язаних секцій. Під час дослідження ефективності U-подібних екранів також варіювалися довжина і число проводів рукавів. Показано доцільність використання екрану, що складається з двох електрично незв’язаних секцій. Однією секцією є перемичка U-подібного екрану, іншою – рукава екрану, з’єднані паралельно. Також показано, що число проводів рукава може бути зменшено до п'яти за умови збереження його металоємності. Бібл. 10, рис. 3, табл. 1.

Ключові слова: лінія електропередачі, магнітне поле, екранування, гранично допустимий рівень.

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