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EFFICIENT SHIELDING OF THREE-PHASE CABLE LINE MAGNETIC FIELD BY PASSIVE LOOP UNDER LIMITED THERMAL EFFECT ON POWER CABLES

This paper deals with a mitigation of a three-phase cable line magnetic field by a new type of passive shield. We consider a cable line with a flat arrangement of cables. The developed single-loop shield has an asymmetric magnetic coupling with the cable line, due to the use of two different ferromagnetic cores. Its high shielding efficiency is experimentally confirmed. As the developed shield is 0.2÷0.3 m away from the cable line, its thermal effect on the cable line is negligible. As the result, we obtain expressions for the shielding efficiency, parameters of the shield and the cores. References 18, figures 5.
Index terms: **cable line, magnetic field, passive loop, shielding, magnetic core.**

Запропоновано новий тип пасивного екрану для зменшення магнітного поля трифазних кабельних ліній електропередачі із прокладанням кабелів за схемою «у площині». Розроблений одноконтурний екран має несиметричний магнітний зв'язок з кабельною лінією, обумовлений використанням двох різних феромагнітних осердь, та характеризується підтвердженою експериментально високою ефективністю екранування при мінімальному тепловому впливі на кабельну лінію за рахунок віддалення від неї екранних кабелів на відстань 0,2÷0,3 м. Отримано співвідношення для визначення ефективності екранування, параметрів екрану та осердь. Бібл. 18, рис. 5.
Ключові слова: **кабельна лінія, магнітне поле, екранування, контурний екран, феромагнітне осердя.**

Предложен новый тип пассивного экрана для уменьшения магнитного поля трехфазных кабельных линий электропередачи с прокладкой кабелей по схеме «в плоскости». Разработанный одноконтурный экран имеет несимметричную магнитную связь с кабельной линией, обусловленную использованием двух разных ферромагнитных сердечников, и характеризуется подтвержденной экспериментально высокой эффективностью экранирования при минимальном тепловом воздействии на кабельную линию за счет удаления от нее экранных кабелей на расстояние 0,2÷0,3 м. Получены соотношения для определения эффективности экранирования, параметров экрана и сердечников. Библ. 18, рис. 5.
Ключевые слова: **кабельная линия, магнитное поле, экранирование, контурный экран, ферромагнитный сердечник.**

Introduction. High-voltage three-phase cable lines are widely used in developed countries for the electric energy transmission in cities, and as well they have good prospects in Ukraine. The fact is that cable lines have several advantages over traditional overhead lines.

Firstly, the width of the protection zone of widely used in cities 110 kV overhead lines is 40 m, while the width of the protection zone of 110 kV cable lines does not exceed 2 m [1]. Therefore, the cable line route does not require the alienation of large and expensive urban land. Secondly, the magnetic field level of overhead lines does not meet modern requirements in terms of environmental safety. According to [1, 2] the power frequency magnetic field should not exceed 0.5 μT in a living space and 10 μT in an urban area. In [3, 4] it was shown experimentally and by numerical simulation, that the magnetic field can exceed the reference level of 0.5 μT in houses located near overhead lines. At the same time, this standard is usually fulfilled for the cable line magnetic field, since the distance between cables is an order less than the distance between overhead line conductors. So the magnetic field decreases faster when moving away from the cable line [5].

However the magnetic field often exceeds the reference level of 10 μT for urban areas directly above the cable line. Modern three-phase cable lines are made of single-core cables with XLPE insulation. The distance between cables is at least 0.5 m [1, 2] in junction zones of 35÷110 kV cable lines. In this case the magnetic field can exceed the allowable level more than 4 times, that forces to take measures to reduce it.

Various types of passive shields [6–12] and systems of active shielding [13, 14] are used to reduce the cable line magnetic field. An advantage of passive shields is the absence of electrical energy sources, used in active systems to create a compensating magnetic field. By the criteria of operating principle, passive shields can be divided into electromagnetic shields [6, 7], magnetic shields [8, 9], and passive loops [10–12]. The most technologically advanced shield is a passive loop type HMCPL with ferromagnetic elements, through the use of which a relatively high efficiency of the magnetic field shielding is achieved [10, 11]. Fig. 1 shows an example of a practical implementation of HMCPL. A significant disadvantage of this type of shield is a proximity of cables of the shield to cables of the cable line, that is necessary to ensure the required shielding efficiency. This leads to the additional heating of the cable line and to the reducing of its capacity.

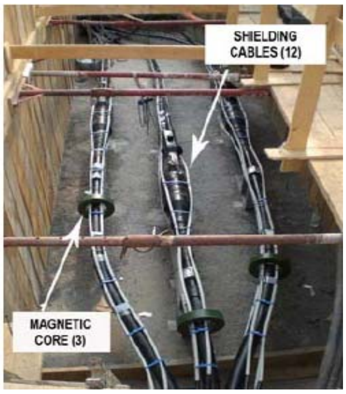

Fig. 1. Passive loop type HMCPL with ferromagnetic cores and cables of shield arranged on cable line

The goal of the paper is the development of a passive loop to reduce the magnetic field in junction zones of cable lines, that has a minimal thermal effect on the cable line while maintaining high shielding efficiency.

The object of the study is the magnetic field of the cable line with flat arrangement of cables used in junction zones [1, 2].

The main idea of this work is to use a shield made of a passive loop and two ferromagnetic cores to compensate the dipole component of the cable line magnetic field (Fig. 2). The dipole component prevails at reference points, that are distant from the cable line by two cable line width or more. Wherein cables of the shield are 0.2÷0.3 m away from the cable line, that allows to minimize the thermal effect. Ferromagnetic cores enhance the magnetic coupling between the shield and the cable line and ensure high shielding efficiency.

Single-loop shield with ferromagnetic cores and asymmetric magnetic coupling with cable line. It was shown in [15] that the Clarke transformation allows to represent three-phase current as a superposition of three components: α-, β-, and "zero" component. If the power line is symmetrical, the currents of the "zero" component are equal to zero. Based on this, in [16] the magnetic field of a three-phase power line with the conductors arranged in the same plane (horizontal or vertical) is considered as a superposition of the α- and β-component of the magnetic field, which are created by the corresponding current components. Also it was shown that the β-component of the magnetic field is several times greater than the α-component. A qualitative explanation is given in [17]. It is noted that the β-component of the cable line magnetic field is essentially its dipole component.

According to [15], the β-component of currents of the flat cable line flows in a closed contour formed by conductors of two outer cables. The amplitude of the β-component current is $\sqrt{3}/2$ times greater than the amplitude of the conductor current, and the phase shift relative to the conductor current is $\pm\pi/6$ depending on the cable. To compensate the β-component of the cable line magnetic field, sections P_1P_2 and P_3P_4 of the proposed single-loop shield (Fig. 2, *a*) are parallel to the cable line. These sections are distant from the cable line and they are arranged at some height H to minimize the thermal effect of the shield currents on the cable line.

The length of sections P_1P_2 and P_3P_4 is denoted by l. The characteristic dimensions of sections P_4P_1 and P_2P_3 are much smaller than l, so l can be considered as the length of the shield.

Two ferromagnetic cores are installed on outer cables in the section P_4P_1. Each core covers the shield cable and the corresponding cable of the cable line. Each core is splittable to simplify the installation of the proposed single-loop shield (Fig. 2, *b*). Marking letters of cores correspond to cables of the cable line. Each core is characterized by three parameters: effective magnetic permeability μ, cross-section S_{core} and length l_{core} of the core midline.

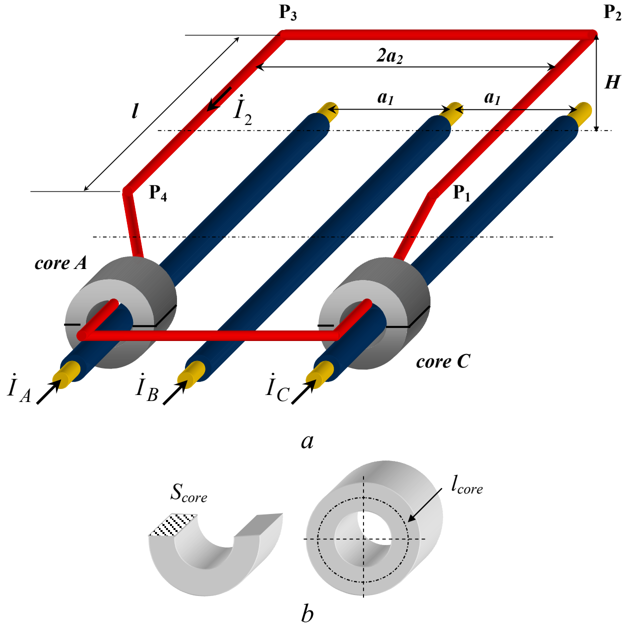

Fig. 2. Design of proposed single-loop shield (*a*) with ferromagnetic cores (*b*)

In general, the presented single-loop shield is characterized by the following parameters:

– the height H of the arrangement above the cable line;

– the width $2a_2$ of the shield (the distance between parallel sections P_1P_2 and P_3P_4);

– the length l of the shield (the length of sections P_1P_2 and P_3P_4);

– conductivity σ and cross-sectional radius r of the shield cables;

– set of parameters μ, S_{core}, l_{core} for each of cores (where the index "*core*" takes values *A* and *C* for the core on the left and right cable, respectively).

Single-loop shield efficiency. Since the shield length l is several times greater than $2a_2$ and the characteristic dimension of the section P_4P_1, then we analyze the magnetic field in the two-dimensional approximation. We choose the coordinate system with the abscissa axis located 0.5 m height above the ground level. So the abscissa axis matches the reference plane of the magnetic field normalization. The ordinate axis passes through the central cable of the cable line (Fig. 3). Then among the points from the x-axis, the non-shielded magnetic field of the cable line is maximum at the origin.

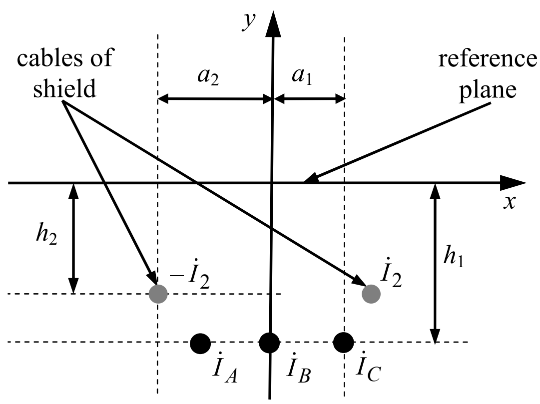

Fig. 3. Cross-section of cable line (black points) and cables of single-loop shield (gray points)

We consider a three-phase cable line with a positive sequence of conductor currents. Then current phasors in cables of the cable line are the following:

$$\dot{I}_A = \sqrt{2}\, I\, e^{-j\cdot\frac{2\pi}{3}}\ ,\ \ \dot{I}_B = \sqrt{2}\, I\ ,\ \ \dot{I}_C = \sqrt{2}\, I\, e^{j\cdot\frac{2\pi}{3}}\ , \qquad (1)$$

where I is the RMS current in the cable line; j is an imaginary unit.

Applying the Clarke transform to the system of currents (1) and calculating the RMS values of α- and β-components of the cable line magnetic field at the origin, we obtain:

$$B_\alpha = \frac{\mu_0 I}{2\pi h_1}\cdot\frac{a_1^2}{a_1^2+h_1^2}\ ,\ \ B_\beta = \sqrt{3}\cdot\frac{\mu_0 I}{2\pi h_1}\cdot\frac{a_1 h_1}{a_1^2+h_1^2}\ , \qquad (2)$$

where h_1 is the distance from the cable line to the reference plane of the magnetic field normalization; a_1 is the distance between adjacent cables of the cable line; $\mu_0=4\pi\cdot10^{-7}$ H/m is a vacuum permeability.

Since vectors of the α- and β-components of the cable line magnetic field are mutually perpendicular at the origin, then the magnetic field is equal to the square root of the sum of squares B_α and B_β. We obtain the expression for the maximum shielding factor SF from (2) and the accepted assumption about the compensation of the β-component magnetic field by the single-loop shield:

$$SF = \frac{\sqrt{B_\alpha^2 + B_\beta^2}}{B_\alpha} = \sqrt{1+3\cdot\left(\frac{h_1}{a_1}\right)^2}\ . \qquad (3)$$

To reach the maximum shielding factor, the field created by the single-loop shield at the origin must be opposite to the β-component of the cable line magnetic field. This condition gives the expression for the required phasor current in the single-loop shield:

$$\dot{I}_2 = -\dot{I}_1\cdot\frac{a_1}{a_2}\cdot\frac{a_2^2+h_2^2}{a_1^2+h_1^2}, \qquad (4)$$

where h_2 is the distance from shield cables to the reference plane; $\dot{I}_1 = j\sqrt{\frac{3}{2}}\,I$ is the phasor of the β-component of cable line currents.

Note that the height of the arrangement of the shield above the cable line (outside the core location area) is $H=h_1-h_2$.

Calculation of parameters of ferromagnetic cores. We use the approach from [18] to analyze the current induced in the single-loop shield. Using complex forms of Ohm's law and Faraday's law of induction, we write down the following relation for a closed contour of the shield:

$$\dot{I}_2\cdot 2R = -j\,\omega\cdot\left(\dot{\Phi}_1+\dot{\Phi}_2+\dot{\Phi}_A+\dot{\Phi}_C\right), \qquad (5)$$

where $R = l/\left(\sigma\pi r^2\right)$ is a DC resistance of the section P_1P_2; $\omega=2\pi\cdot50$ s^{-1} is an angular current frequency; $\dot{\Phi}_1, \dot{\Phi}_2$ are phasors of magnetic flux of cable line currents and shield currents, respectively, through the closed contour of the shield; $\dot{\Phi}_A, \dot{\Phi}_C$ are phasors of magnetic flux running through A and C cores located on the left and on the right cables, respectively.

Expressions for magnetic fluxes have the following form:

$$\begin{aligned}
&\dot{\Phi}_1 = M\cdot\dot{I}_1\ ,\ \ M = l\cdot\frac{\mu_0}{2\pi}\cdot\ln\frac{(a_1+a_2)^2+(h_1-h_2)^2}{(a_1-a_2)^2+(h_1-h_2)^2}\ ,\\
&\dot{\Phi}_2 = L\cdot\dot{I}_2\ ,\ \ L = l\cdot\frac{\mu_0}{\pi}\cdot\left(\frac{1}{4}+\ln\frac{2\,a_2}{r}\right),\\
&\dot{\Phi}_A = -L_A\cdot\left(\dot{I}_A-\dot{I}_2\right),\ \ L_A = \frac{\mu\mu_0 S_A}{l_A}\ ,\\
&\dot{\Phi}_C = L_C\cdot\left(\dot{I}_C+\dot{I}_2\right),\ \ L_C = \frac{\mu\mu_0 S_C}{l_C}\ .
\end{aligned} \qquad (6)$$

We substitute (6) into (5) and solve the resulting equation with respect to $\dot{I}_2$. Comparing (4) and the solution, we obtain the following:

$$\begin{cases}
L_A - L_C = \dfrac{2\sqrt{3}\,R}{\omega}\cdot\dfrac{a_1}{a_2}\cdot\dfrac{a_2^2+h_2^2}{a_1^2+h_1^2}\ ,\\
L_A + L_C = -\dfrac{\omega(L_A-L_C)L - 2\sqrt{3}\,R\,M}{\omega(L_A-L_C)-2\sqrt{3}\,R}\ .
\end{cases} \qquad (7)$$

The expressions (6)–(7) allow to calculate values of inductances introduced by ferromagnetic cores and to determine their parameters. Note that inductances L_A and L_C can take both positive or negative values. The inductance sign determines the mutual orientation of the core and the shield contour (Fig. 4).

In general, values of L_A and L_C are different and can differ by an order or more. This is one of the characteristic features of the proposed shield, that can be classified as a single-loop shield with asymmetric magnetic coupling with a cable line.

Design features of single-loop shield with asymmetric magnetic coupling. There are two competing factors when choosing the height H of the shield above the cable line and the width $2a_2$ of the shield. On the one hand, a decrease of these parameters leads to an increase of the required shield current according to (4). Also it leads to the convergence of the shield and the cable line. Accordingly, the thermal effect on the cable line increases. On the other hand, the analysis of the magnetic field distribution along the x-axis shows that the decrease of H and $2a_2$ allows to ensure the high shielding efficiency of the magnetic field in a wider region.

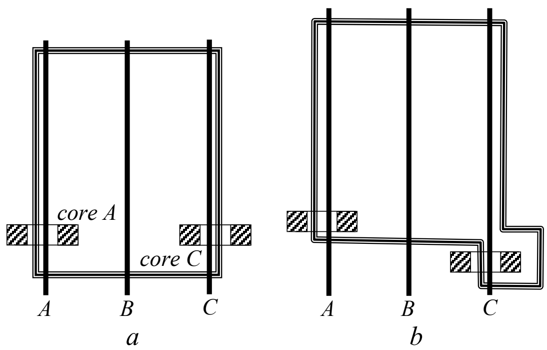

Fig. 4. Mutual orientation of cores and shield contour: (a) $L_A>0$, $L_C>0$; (b) $L_A>0$, $L_C<0$

The carried out analysis together with the results of the heat problem solution, which are not presented in this paper, allow to recommend H=0.4·a_1÷0.6·a_1, a_2=1.5·a_1. In other words, if the distance between adjacent cables of the cable line is taken as a unit of length, then the recommended width of the shield is 3 units, and it is recommended to arrange cables of the shield at a height of 0.4÷0.6 units above the cable line. At these conditions the shield practically does not affect the thermal mode of the cable line.

The technique from [2] can be used to find the length l of the shield (Fig. 2).

The required inductances L_A and L_C of ferromagnetic cores used in the shield design are calculated using (7).

If L_A and L_C are positive, then cores are installed as shown in Fig. 4, *a*. If one of the values is negative, then the orientation of the shield current direction relative to the core should be reversed. In this case, the mutual arrangement of cores and the shield contour is shown in Fig. 4, *b*.

The magnetic permeability, the cross-sectional area, and the length of the midline of each core are chosen according to (6) based on the absolute value of its inductance.

A full-scale model of the proposed single-loop shield with asymmetric magnetic coupling was experimentally studied. An experimental setup contains a 10 m long physical model of a three-phase cable line (Fig. 5). The reference plane of the magnetic field normalization is 2 m height above the cable line, the distance between adjacent cables is 0.5 m. The loop of the shield is made of a single-core copper cable. Cores are made of transformer steel. The experiment was carried out when the width of the shield is 1.5 m and the height of shield arrangement above the cable line is 0.3 m. The experimentally confirmed shielding efficiency of the magnetic field is 7.

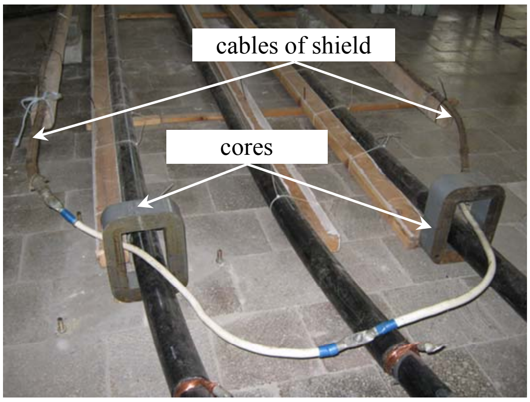

Fig. 5. Experimental setup for studying efficiency of shielding of cable line magnetic field by single-loop shield with asymmetric magnetic coupling

Conclusions.

1. We propose a single-loop shield with ferromagnetic cores and asymmetric magnetic coupling. It ensures high shielding efficiency of the magnetic field, and it is distant from the cable line by a height equal to 0.4÷0.6 of the distance between adjacent power cables. This allows to minimize the thermal effect on the cable line in comparison with known passive loops having similar shielding efficiency.

2. We theoretically justified and experimentally confirmed that the shielding factor is equal to 7, when the distance between adjacent cables of the cable line is 0.5 m (typical for junction zones), the recommended width of the shield is 1.5 m, the shield is 0.3 m height above the cable line, and the reference plane of the magnetic field normalization is 2 m height above the cable line.

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