EFFICIENT SHIELING 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.

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

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The characteristic dimensions of sections P4P1 and P2P3 permeability characterized by three parameters: effective magnetic cores correspond to cables of the cable line. Each core is proposed single-loop shield (Fig. 2, the core is splittable to simplify the installation of the cable and the corresponding cable of the cable line. Each core covers the shield length of the shield. 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 P1P2 and P3P4 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 P1P2 and P3P4 is denoted by $l$. The characteristic dimensions of sections P2P1 and P3P1 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 P1P1. 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 $\mu$, cross-section $S_{core}$ and length $l_{core}$ of the core midline.

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 P1P2 and P3P4);
- the length $l$ of the shield (the length of sections P1P2 and P3P4);
- conductivity $\sigma$ and cross-sectional radius $r$ of the shield cables;
- set of parameters $\mu$, $S_{core}$, $l_{core}$ 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 P2P1, 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.
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:

\[ i_A = \sqrt{2} I e^{-j \frac{2\pi}{3}}, \quad i_B = \sqrt{2} I e^{j \frac{2\pi}{3}}, \quad i_C = \sqrt{2} I e^{j \frac{2\pi}{3}}, \]

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 \( \alpha \)- and \( \beta \)-components of the cable line magnetic field at the origin, we obtain:

\[ B_\alpha = \frac{\mu_0 I}{2\pi h_1} \frac{a_1^2}{a_1^2 + h_1^2}, \quad B_\beta = \sqrt{3} \frac{\mu_0 I}{2\pi h_1} \frac{a_1 h_1}{a_1^2 + h_1^2}, \]

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; \( \mu_0 = 4\pi \times 10^{-7} \text{H/m} \) is a vacuum permeability.

Since vectors of the \( \alpha \)- and \( \beta \)-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

\[ \Phi_\alpha = -\Phi_\beta \left( h_1 - h_2 \right), \quad |\Phi_\beta| = |\Phi_\alpha| \left( 1 + \ln \frac{a_2}{a_1} \right), \]

we obtain:

\[ \Phi = \frac{\left( h_1 - h_2 \right)}{\left( 1 + \ln \frac{a_2}{a_1} \right)}, \]

where vectors of the \( \alpha \)- and \( \beta \)-components of the cable line magnetic field at the origin, \( \Phi_\alpha \) and \( \Phi_\beta \), to the reference plane and \( \Phi_\alpha \) is the phasor of the \( \beta \)-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:

\[ \int_{i_1}^{i_2} i \cdot 2 R = -j \omega \left( \Phi_1 + \Phi_2 + \Phi_A + \Phi_C \right), \]

where \( R = \frac{1}{P_1 P_2} \) is a DC resistance of the section \( P_1 P_2 \); \( \omega = 2\pi f \) is an angular current frequency; \( \Phi_1, \Phi_2 \) are phasors of magnetic flux of cable line currents and shield currents, respectively, through the closed contour of the shield; \( \Phi_A, \Phi_C \) 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:

\[ \Phi_1 = M \cdot I_1, \quad M = l \frac{\mu_0}{2\pi} \ln \frac{a_1 + a_2}{(a_1 - a_2)} \frac{(h_1 - h_2)^2}{(a_1 - a_2)^2 + (h_1 - h_2)^2}, \]
\[ \Phi_2 = L \cdot I_2, \quad L = l \frac{\mu_0}{\pi} \left( 1 + \ln \frac{a_2}{r} \right), \]
\[ \Phi_A = -L \left( I_1 - I_2 \right), \quad L = \frac{\mu_0 S_A}{I_A}, \]
\[ \Phi_C = L \left( I_1 + I_2 \right), \quad L = \frac{\mu_0 S_C}{I_C}. \]

We substitute (6) into (5) and solve the resulting equation with respect to \( I_2 \). Comparing (4) and the solution, we obtain the following:

\[ \left\{ \begin{array}{l}
L_A - L_C = \frac{2\sqrt{3} R}{\omega} \frac{a_1}{a_2} - \frac{a_2^2}{a_1^2} + h_2^2 \frac{a_1}{a_1^2 + h_1^2}, \\
L_A + L_C = -\frac{2\sqrt{3} R}{\omega} \left( L_A - L_C \right) - 2\sqrt{3} RM.
\end{array} \right. \]

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) \( L_A<0, L_C>0 \).](image-url)
The carried out analysis together with the results of the heat problem solution, which are not presented in this paper, allow to recommend \( H=0.4a_1+0.6a_2 \). 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 experiment was carried out when the width of the shield is 1.5 m and the height of the midline of each core are calculated using (7).

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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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REFERENCES

1. Electrical installation regulations. 5th ed. Kharkiv, Minenergovugillya of Ukraine, 2014. 793 p. (Ukr).
2. SOU-N MEV 40.1-37471933-49:2011.2. Design of cable lines with voltage up to 330 kV. Guidance. Kyiv, Minenergovugillya of Ukraine Publ., 2017. 139 p. (Ukr).
3. Pelevin D.Ye. Screening magnetic fields of the power frequency by the walls of houses. Electrical Engineering & Electromechanics, 2015, no.4, pp. 53-55. (Ukr).
4. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.
5. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.
6. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.
7. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.
8. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.
9. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.
10. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.
11. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.
12. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.
13. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.
14. Hou W., Li Y., Liu Y., Yu X. A new approach for the design of high-frequency transformers. IEEE Transactions on Power Delivery, 2012, vol.27, no.4, pp. 1874-1880.

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

Conclusions.

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mitigation in power systems. *Energies*, 2019, vol.12, no.7, p. 1332. doi: 10.3390/en12071332.

15. Duesterhoeft W.C., Schulz M.W., Clarke E. Determination of instantaneous currents and voltages by means of alpha, beta, and zero components. *Transactions of the American Institute of Electrical Engineers*, 1951, vol.70, no.2, pp. 1248-1255. doi: 10.1109/T-AIEE.1951.5060554.

16. Walling R.A., Paserba J.J., Burns C.W. Series-capacitor compensated shield scheme for enhanced mitigation of transmission line magnetic fields. *IEEE Transactions on Power Delivery*, 1993, vol.8, no.1, pp. 461-469. doi: 10.1109/61.180369.

17. Rozov V., Grinchenko V., Tkachenko O., Yerisov A. Analytical calculation of magnetic field shielding factor for cable line with two-point bonded shields. *IEEE 17th International Conference on Mathematical Methods in Electromagnetic Theory*, 2018, pp. 358-361. doi: 10.1109/MMET.2018.8460425.

18. Rozov V.Yu., Grinchenko V.S., Tkachenko A.O. Calculation of magnetic field of three-phase cable lines with two-point bonded cable shields covered by ferromagnetic cores. *Electrical Engineering & Electromechanics*, 2015, no.5, pp. 44-47. (Rus). doi: 10.20998/2074-272X.2017.5.06.

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