Reduction of High-Voltage Cable Line Capacity Caused by Implementation of Magnetic Field Shielding Techniques

Grinchenko V. [1], **Tkachenko O.** [2]
[1] General Energy Institute of National Academy of Sciences of Ukraine, Kyiv, Ukraine
[2] Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine, Kharkiv, Ukraine

Abstract. The paper deals with a capacity of high-voltage cable line made of three single-core cross-linked polyethylene insulated power cables. We consider three cases. First is a single-point bonded cable system when no magnetic field shielding technique is implemented and the capacity achieves maximum values. Second is a solidly bonded cable system when a thermal effect of induced shield currents causes a capacity reduction. The third case under study is a single-point bonded cable system covered by the passive loop. The passive loop mitigates the cable line magnetic field as well as the solidly bonding does, but also the thermal effect of passive loop currents reduces the capacity. The goal of the paper is to evaluate the relative change of cable line capacity when implementing magnetic field shielding techniques comparably to unshielded case. To achieve the goal we use a standard IEC 60287 when calculating the cable line capacity in the first and the second cases, and a thermal field simulation in the third case. The capacity is evaluated by successive approximations. Iterations are stopped when the conductor reaches the maximum operating temperature. We show that the increase in cable spacing does not guarantee the capacity increase when the solid bonding of cable shields or the passive loop is used. The most significant result is the substantiation of the advantages of passive loop, which provides the greater capacity in comparison with solid bonding at equivalent magnetic field shielding efficiencies. The obtained results can be used when choosing the type of bonding and the technique of cable line magnetic field mitigation.

***Keywords*:** cable line, capacity, magnetic field, shielding, passive loop, bonding.

DOI: https://doi.org/10.52254/1857-0070.2023.3-59.04
UDC: 621.315.23:621.3.017.73

Reducerea capacității liniei de cablu de înaltă tensiune prin ecranarea câmpului magnetic al lui

Grinchenko V.S. [1], **Tkachenko O.O.** [2]
[1] Institutul de Energetică generală al Academiei Naționale de Științe a Ucrainei, Kiev, Ucraina
[2] Anatolii Pidhornyi Institutul de Probleme de Inginerie Mecanică al Academiei Naționale de Științe a Ucrainei, Harkiv, Ucraina

Rezumat. Lucrarea tratează o capacitate de linie de cablu de înaltă tensiune formată din trei un singur conductor cabluri de alimentare cu izolare din polietilenă reticulat. Luăm în considerare trei cazuri. Mai întâi este un sistem de cabluri conectate într-un singur punct când nu este implementată nicio tehnică de ecranare a câmpului magnetic şi capacitatea atinge valorile maxime. Al doilea este un sistem de cablu solid legat atunci când un efect termic al curenților induși de ecranare determină o reducere a capacității. Al treilea caz studiat este un sistem de cabluri conectate într-un singur punct acoperit de bucla pasivă. Bucla pasivă atenuează câmpul magnetic al liniei de cablu, așa cum o face legătura solidă, dar și efectul termic al curenților buclei pasive reduce capacitatea. Scopul lucrării este de a evalua modificarea relativă a capacității liniei de cablu atunci când diferite tehnici de ecranare a câmpului magnetic sunt implementate în mod comparabil cu carcasa neecranată. Pentru a atinge obiectivul, folosim un standard IEC 60287 atunci când calculăm capacitatea liniei de cablu în primul și al doilea caz și folosim o simulare de câmp termic atunci când este utilizată bucla pasivă. Cel mai semnificativ rezultat este fundamentarea avantajelor buclei pasive, care oferă o capacitate mai mare a liniei de cablu în comparație cu legăturile solide la eficiențe echivalente de ecranare a câmpului magnetic. Rezultatele obținute pot fi utilizate la alegerea tipului de legare și a tehnicii de atenuare a câmpului magnetic al liniei de cablu.

Cuvinte-cheie: linie de cablu, capacitate, câmp magnetic, ecranare, buclă pasivă, legare.

Снижение пропускной способности кабельной линии высокого напряжения при экранировании ее магнитного поля

Гринченко В.С. [1]**, Ткаченко А.О.** [2]
[1] Институт общей энергетики Национальной академии наук Украины, Киев, Украина
[2] Институт проблем машиностроения им. А.Н. Подгорного Национальной академии наук Украины
Харьков, Украина

Аннотация. В статье исследована пропускная способность кабельной линии высокого напряжения, состоящей из трех одножильных силовых кабелей со сшито-полиэтиленовой изоляцией. Рассмотрены три случая. В первом случае, когда выполнено одностороннее заземление экранов кабелей, а магнитное поле кабельной линии не экранируется, пропускная способность достигает максимальных значений. Во втором, когда выполнено двустороннее заземление, тепловое действие токов, наведенных в экранах кабелей, вызывает снижение пропускной способности. В третьем случае рассмотрена кабельная линия с односторонним заземлением экранов кабелей, на которой расположен пассивный контурный экран. Контурный экран, как и двустороннее заземление собственных экранов кабелей, позволяет уменьшить магнитное поле кабельной линии, но тепловое действие его токов также вызывает снижение пропускной способности. Целью статьи является оценка относительного изменения пропускной способности кабельной линии при экранировании ее магнитного поля по сравнению со случаем, когда снижения магнитного поля не проводится. Поставленная цель достигается путем применения стандарта IEC 60287 для определения пропускной способности в первом и втором случаях, а также численного моделирования теплового поля кабельной линии при использовании контурного экрана. При этом пропускная способность находится методом последовательных приближений, а итерационный процесс прекращается при достижении в жилах кабелей максимальной рабочей температуры. При исследовании пропускной способности варьируются следующие параметры: удельное тепловое сопротивление грунта, расстояние между кабелями, сечение жилы кабелей и сечение экранов. Показано, что увеличение расстояния между кабелями не гарантирует увеличения пропускной способности как при двустороннем заземлении экранов кабелей, так и использовании контурного экрана. Наиболее существенным результатом является обоснование преимущества применения контурного экрана, обеспечивающего большую пропускную способность кабельной линии в сравнении с двусторонним заземлением при эквивалентных эффективностях экранирования магнитного поля. Значимость полученных результатов состоит в возможности их использования при выборе типа заземления и способа экранирования магнитного поля кабельной линии.

Ключевые слова: кабельная линия, пропускная способность, магнитное поле, экранирование, контурный экран, заземление.

I. INTRODUCTION

The most advanced means of electrical energy transmission in urban areas are underground high-voltage cable lines. The economic reason is an important one, as the cable line does not require significant land allocation when a power line route crosses residential area. For example, according to the Ukrainian regulations [1] the border zone is 20 m for 110 kV overhead lines and only 2 m for 110 kV cable lines. As well the electromagnetic safety reason becomes important for last decades. The potential risks of long-term exposure of a power frequency magnetic field to human health are discussed in [2-4]. The problem is studied by the World Health Organization within the “The International EMF Project”. In Ukraine, the maximum permissible level (so-called reference level) of the power frequency magnetic field is 0.5 μT for living spaces and 10 μT for residential areas [1]. In general, the reference levels in Ukraine correspond to the current global trend towards stricter standards [5].

It is shown in [6-8] that 110 kV overhead line magnetic field exceeds the referred above reference level for living spaces outside its right-of-way. Therefore, the impermissible level of magnetic field is observed in high-rise buildings. This information can be represented on geoinformation maps [9-11]. In contrast, the cable line magnetic field could exceed the reference level for living spaces only on the ground floor [12]. In the right-of-way the cable line magnetic field could exceed the reference level for residential areas. The magnetic field highest level is observed in junction zones where the cable spacing reaches 0.5 m [1].

A typical high-voltage cable line consists of three single-core, cross-linked polyethylene (XLPE) insulated power cables. Fig. 1 shows main elements of 110 kV power cable, namely aluminum or copper conductor, XLPE insulation, and copper shield (a.k.a. shield of cable). Shields of cables require earthing. For this they are bonded and earthed at one or several points.

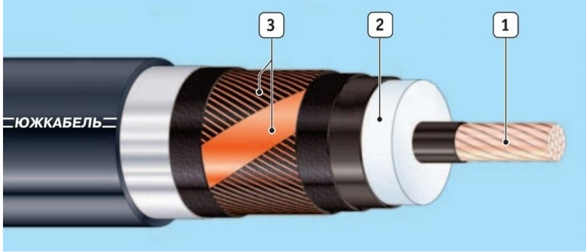


Fig. 1. Power cable for rated voltage 110 kV (1 – conductor, 2 – XLPE insulation, 3 – shield).

Different types of bonding are known [13-15], but the common ones are as follows [1]: single-point bonding, cross-bonding, and solid bonding. Single-point bonding and cross-bonding provides no circulating shield currents and consequently no extra heating of cables. This allows achieving the highest cable line capacity. However, single-point bonded and cross-bonded cable systems require additional protective devices. The solidly bonded cable system is free of this disadvantage, but another one appears. Thus, the thermal effect of shield currents leads to the cable line capacity reduction. On the other hand, the magnetic field of induced currents mitigates the total magnetic field of the cable line. This technique of mitigation of the cable line magnetic field is included to [16], but its effect on the cable line capacity is not studied.

Another way to mitigate the magnetic field of single-point bonded or cross-bonded cable system is to use an extra shield. Traditionally electromagnetic shields made of aluminum [17-20] and magnetic shields with high permeability [19-22] are used. Usually these shields are plane, U-shaped, H-shaped or they enclose the cable line. Neglecting the hysteresis loses, the magnetic shields do not produce heat. Thermal effect of Joule heating of electromagnetic shields on the cable line is negligible as the shield is distant by 200 mm from the power cable. So electromagnetic and magnetic shields do not reduce the cable line capacity. But they have two disadvantages, namely the quantity of metal is relatively high and the solid construction makes it difficult to access the cable line.

Shields made of passive loops are free of these disadvantages. There are single-loop shields [23-25], double-loop shields [25-27], and multi-loop shields [26, 27]. It is shown in [23] that a single-loop shield with an asymmetric magnetic coupling efficiently mitigates the magnetic field in the junction zone of cable line, and it does not lead to the cable line capacity reduction. Similar passive loops covering long sections of high-voltage cable lines are shown in [28] and [29]. However, the single-loop shield covering the long section of cable line is not discussed and its thermal effect on the cable line capacity in such case is not studied.

The goal of the paper is to evaluate the relative change of cable line capacity when implementing magnetic field shielding techniques comparably to unshielded case.

Namely, the capacity reduction caused by solid bonding of the shields of cables and the reduction caused by usage of the long single-loop shield with an asymmetric magnetic coupling (hereinafter referred to as the passive loop) are under study. To assess the capacity reduction, we find the capacity of single-point bonded cable system and the capacity reduced by the thermal effect of closely located shielding conductors. These shielding conductors are the shields of cables (when the cable system is solidly bonded) or the conductors of passive loop (when it covers the cable line). To evaluate the cable line capacity, we use both the standard IEC 60287 “Electric cables – Calculation of current rating” and the technique based on the numerical simulation.

II. CALCULATION OF CABLE LINE CAPACITY BY IEC 60287 STANDARD

The IEC 60287 standard makes it possible to calculate the cable line capacity when the system is single-point bonded or solidly bonded. We examine the capacity of 110 kV cable line for two conductor sizes. As well two sizes of cable shield cross-section and two variants of cable spacing are under study.

The parameters of the cable line and the ambient are as follows:

– load factor is 100%;

– cable line is flat and cables are buried 1.5 m deep;

– distance between axis of adjacent power cables (so-called cable spacing) equals two or four diameters of the cable;

– soil thermal resistivity ρ_{soil} takes on the values from 0.6 K·m/W to 1.2 K·m/W with the step of 0.2 K·m/W, and 3.0 K·m/W as an extreme case;

– temperature at ground surface is θ_a=20°C.

We model the power cable as a cylindrical conductor coated with three layers, namely the XLPE insulation, the shield, and the jacket as an outer layer. At that the parameters of 110 kV single-core XLPE-insulated power cables are as follows:

– conductor size is 240 mm^2 or 500 mm^2;

– conductor is aluminum;

– maximum operating temperature of conductor is 90°C;

– cable insulation thickness is 16 mm;

– thermal resistivity of cable insulation is 3.5 K·m/W;

– the shield size is 100 mm^2 or 200 mm^2;

– jacket (PVC-insulation) thickness is 4.0 mm;

– thermal resistivity of jacket is 6.0 K·m/W.

According to the subsection 1.4.1.1 of IEC 60287-1-1 standard [30], the permissible current rating is calculated by the following expression:

$$I=\sqrt{\frac{\Delta\theta - W_d\left[0,5T_1+m\left(T_2+T_3+T_4\right)\right]}{RT_1+mR\left(1+\lambda_1\right)T_2+mR\left(1+\lambda_1+\lambda_2\right)\left(T_3+T_4\right)}}, \qquad (1)$$

where $\Delta\theta$ is the permissible temperature rise of conductor above the ambient temperature θ_a, K; R is the alternating current resistance of conductor at its maximum operating temperature, Ω/m; W_d is the dielectric losses per unit length per phase; T_1 is the thermal resistance per unit length between conductor and shield, K·m/W; T_2 is the thermal resistance between shield and armour, K·m/W; T_3 is the thermal resistance of cable jacket, K·m/W; T_4 is the thermal resistance between cable surface and soil, K·m/W; m=1 is the number of conductors in the cable; λ_1 and λ_2 is the ratio of total losses in shield and armour respectively to total conductor losses.

As the power cables under study have no armor, then parameters T_2 and λ_2 are equal to zero. We find the parameters T_1, T_3, and T_4 using subsections 2.1.1, 2.1.3, and 2.2.3.2.2 of the standard IEC 60287-2-1 [31].

In the single-point bonded cable system there are no currents in the shields of cables. Correspondingly λ_1=0. Calculating the capacity of cable line with solidly bonded shields according to (1), we use the loss factor λ_1 for the outer cable. It is bigger than the loss factor for the middle cable. By-turn, the bigger loss factor gives the less permissible current rating.

Table 1 shows the calculation results for the cable line capacity when the conductor size is 240 mm^2. It covers two variants of cable spacing, two variants of shield size, and both types of shield bonding. Similar Table 2 shows the capacity when the conductor size is 500 mm^2.

As expected the single-point bonded cable system provides more capacity compared to the solidly bonded one. The capacity does not depend on the shield size when the single-point bonding is used. To increase the capacity, cables with greater conductor cross-section can be used. Comparing first lines from Table 1 and Table 2, we find the one and a half times growth of the capacity. Another way to increase the capacity is to distant cables one from another reducing the mutual heating.

According to [1] the cable spacing of two cable diameters is regular, but its four-time increase is permitted by [16]. Comparing lines no. 1 and no. 4 from Table 1, we find the capacity increase by 3.9…6.3% depending on soil thermal resistivity. The similar analysis of Table 2 shows the capacity increase by 4.6…6.8%.

The solid bonding of shields of cables reduces the cable line capacity. Comparing the 1st line of Table 1 with 2nd and 3rd ones, and 4th line with 5th and 6th, we find the capacity reduction by 11.6…18.8%. The similar analysis of Table 2 shows the capacity reduction by 20.9…30.4%.

Obviously the usage of cables with greater conductor cross-section increases the cable line capacity. Comparing lines no. 2 and no. 3 from Table 1 with corresponding lines from Table 2, we find the capacity growth by 27.4…34.8% depending on soil thermal resistivity and shield size. However, the increase of cable spacing does not guarantee the capacity increase because of two competitive effects. The increase of cable spacing reduces the mutual heating of cables and improves the heat transfer to soil. On the other hand, the increase of cable spacing leads to greater induced currents in shields [32] and correspondently to the more intense Joule heating. Comparing line no. 2 of Table 1 with line no. 5, we find a minor reduction of capacity when the shield size is 100 mm^2. And comparing the line no. 3 of Table 1 with the line no. 6, we find the minor increase of capacity when shield size is 200 mm^2.

The similar analysis of Table 2 shows the same. This means that the competitive effects of capacity increasing and capacity decreasing cancel each other.

Therefore, we obtain that the solid bonding of shields of cables reduces the cable line capacity by 10…30%, and the increase of cable spacing and shield size does not significantly affect the capacity.

Table 1

Cable line capacity calculated by IEC 60287 when conductor size is 240 mm^2.

No.	**Cable spacing, mm**	**Shield size, mm^2**	**Type of cable system**	***I*, A**				
				ρ_{soil}=0.6 K·m/W	**ρ_{soil}=0.8 K·m/W**	**ρ_{soil}=1.0 K·m/W**	**ρ_{soil}=1.2 K·m/W**	**ρ_{soil}=3.0 K·m/W**
1	120	–	single-point bonded	507	462	428	400	271
2		100	solidly bonded	448	405	372	346	231
3		200	solidly bonded	441	398	366	340	226
4	240	–	single-point bonded	527	483	448	420	288
5		100	solidly bonded	446	403	371	346	231
6		200	solidly bonded	450	408	375	350	234

Table 2

Cable line capacity calculated by IEC 60287 when conductor size is 500 mm^2.

No.	**Cable spacing, mm**	**Shield size, mm^2**	**Type of cable system**	***I*, A**				
				ρ_{soil}=0.6 K·m/W	**ρ_{soil}=0.8 K·m/W**	**ρ_{soil}=1.0 K·m/W**	**ρ_{soil}=1.2 K·m/W**	**ρ_{soil}=3.0 K·m/W**
1	135	–	single-point bonded	764	693	638	594	397
2		100	solidly bonded	604	540	493	456	298
3		200	solidly bonded	587	524	478	442	288
4	270	–	single-point bonded	799	728	672	628	424
5		100	solidly bonded	585	524	478	443	290
6		200	solidly bonded	594	532	486	449	295

III. CAPACITY EVALUATION VIA CABLE LINE THERMAL FIELD SIMULATION

Another way to evaluate the cable line capacity is to use the thermal field numerical simulation. We assume the cable line thermal field to be plane-parallel. Therefore, a computational domain is a rectangle and includes cross-sections of cable line, passive loop, and soil. Since the cable line runs in a steady-state, the temperature distribution $\theta(x,y)$ does not change over time, where x and y are Cartesian coordinates of the observation point. The distribution satisfies the stationary heat equation. We take some value of the cable line current rating and find a thermal field distribution around the cable line using the finite element method. This gives the temperature of cable conductor. If it is bigger than the maximum operating temperature of 90°C, we repeat the numerical simulation with a less current rating. Otherwise, we increase the current rating for the next simulation. Repeating the cycle, we find the cable line capacity by successive approximations. This technique allows evaluating the capacity of single-point bonded and solidly bonded cable systems as well as the capacity when the passive loop is used.

Table 3 and Table 4 show the results of capacity evaluation when the conductor size is 240 mm^2 and 500 mm^2, respectively. They correspond to Table 1 and Table 2 in lines dedicated to single-point bonded and solidly bonded cable systems. There is some difference in results obtained by different calculation techniques. When the conductor size is 240 mm^2, the difference in capacities of single-point bonded cable system is negligible. The difference reaches 3.5% when the conductor size is 500 mm^2. We attribute this to the non-uniformity of current density in conductors, which is taken into account in numerical simulation. For the solidly bonded cable system, the difference in capacities calculated in different ways is bigger. It lies within 3.3…7.1% when the conductor size is 240 mm^2, and 5.7…11.1% when the conductor size is 500 mm^2. We explain this by precise expressions for shield currents used in numerical simulation, while the expression given the maximum current is used for every of three shields when calculating by IEC 60287. This also explains the higher values of cable line capacity obtained via numerical simulation. However, the results from Table 3 and Table 4 show the same trends as the results from Table 1 and Table 2. Namely, the solid bonding significantly reduces the cable line capacity, and the increase of cable spacing and shield size almost do not affect the capacity.

Another way to mitigate the cable line magnetic field is to use the passive loop covering the outer power cables. Fig. 2 shows the sketch of arrangement of cable line and passive loop. We consider passive loops having 100 and 200 mm^2 copper conductor and 4 mm thick PVC-insulation. The current in the loop provides an extra heating of cable line and reduces its capacity. We assume that the loop current is equal to the β-component obtained as a result of the Clarke transformation [33, 34] applied to the shield currents of the solidly bonded cable system.

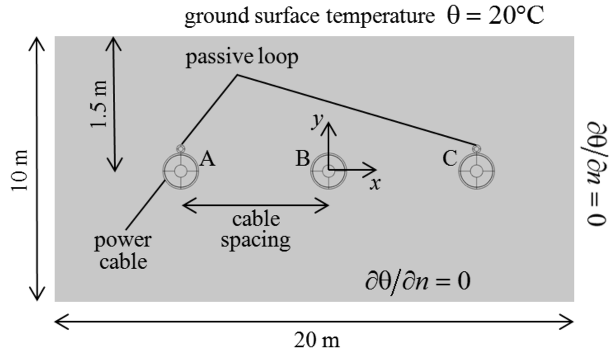


Fig. 2. Sketch of arrangement of cable line and passive loop covering the outer power cables.

This allows equalizing the magnetic field shielding efficiencies in the solidly bonded case and when the passive loop is used.

Analyzing Table 3 and comparing in pairs lines no. 2 and 3, lines no. 4 and 5, lines no. 7 and 8, and lines no. 9 and 10, we find that the implementation of the passive loop ensures more cable capacity than the solid bonding. For example, the solid bonding reduces the capacity by 9.3% and the passive loop reduces the capacity by 5.8% when cable spacing is 120 mm, shield size is 100 mm^2, and soil resistivity ρ_{soil}=1.0 K·m/W. In general Table 3 shows that the capacity is 3.4…9.3% higher when the passive loop is used.

Table 3

Cable line capacity calculated by numerical simulations when conductor size is 240 mm^2.

No.	**Cable spacing, mm**	**Shield size, mm^2**	**Type of cable system**	***I*, A**				
				ρ_{soil}=0.6 K·m/W	**ρ_{soil}=0.8 K·m/W**	**ρ_{soil}=1.0 K·m/W**	**ρ_{soil}=1.2 K·m/W**	**ρ_{soil}=3.0 K·m/W**
1	120	–	single-point bonded	508	464	430	403	277
2		100	solidly bonded	466	423	390	363	247
3			with passive loop	482	438	405	378	257
4		200	solidly bonded	459	416	383	357	242
5			with passive loop	482	438	404	377	256
6	240	–	single-point bonded	529	485	451	423	293
7		100	solidly bonded	465	422	390	363	247
8			with passive loop	497	452	418	391	267
9		200	solidly bonded	465	422	389	363	247
10			with passive loop	501	456	422	394	270

Table 4

Cable line capacity calculated by numerical simulations when conductor size is 500 mm^2.

No.	**Cable spacing, mm**	**Shield size, mm^2**	**Type of cable system**	***I*, A**				
				ρ_{soil}=0.6 K·m/W	**ρ_{soil}=0.8 K·m/W**	**ρ_{soil}=1.0 K·m/W**	**ρ_{soil}=1.2 K·m/W**	**ρ_{soil}=3.0 K·m/W**
1	135	–	single-point bonded	772	701	647	604	411
2		100	solidly bonded	650	584	535	496	331
3			with passive loop	694	624	572	531	355
4		200	solidly bonded	631	567	518	481	320
5			with passive loop	690	620	569	528	353
6	270	–	single-point bonded	807	736	681	636	436
7		100	solidly bonded	630	562	516	479	320
8			with passive loop	701	631	579	538	359
9		200	solidly bonded	628	564	516	479	319
10			with passive loop	713	643	590	549	368

The similar analysis of Table 4 shows the same trend when the conductor size is 500 mm^2. Namely, the cable line with passive loop provides 6.8…15.4% more capacity than the cable line with solidly bonded shields. The excess depends on soil thermal resistivity, cable spacing, and shield size.

The increase in cable spacing and the corresponding increase of width of passive loop covering the cable line do not guarantee the capacity increase because of two competitive effects mentioned before in Section II. Analyzing Table 3 and Table 4 and comparing in pairs lines no. 3 and 5, lines no. 8 and 10, we find that the competitive effects of capacity increasing and capacity decreasing cancel each other and the change of cable line capacity is minor.

IV. CONCLUSIONS

1. Using the IEC 60287 standard and the numerical simulation, we show that 110 kV cable line with solidly bonded shields provides 10…30% less capacity than the single-bonded cable system. The capacity reduction is caused by the thermal effect of currents induced in shields of cables. The rate of reduction depends on power cable parameters, cable spacing, and soil thermal resistivity.
2. The solid bonding of shields of cables leads to the mitigation of cable line magnetic field. However, the passive loop covering the outer power cables is preferable, as the cable line provides up to 15% more capacity in comparison with solid bonding at equivalent magnetic field shielding efficiencies.
3. We show that the increase in cable spacing does not guarantee the capacity increase when the solid bonding of cable shields or the passive loop covering the power cables is used.

ACKNOWLEDGMENT

This work was supported by the project "Optimization of active loop used to mitigate magnetic field of indoor transformer substation" funded by the Ministry of Education and Science of Ukraine and by the project "Refined method of calculating currents in cable shields when earthing a high-voltage cable line at both ends" funded by the National Academy of Sciences of Ukraine.

References

[1] *Electrical installation regulations*. Kharkiv, Fort Publ., 2017, 760 p. (In Ukrainian)

[2] Ates K., Carlak H.F., Ozen S. Dosimetry analysis of the magnetic field of underground power cables and magnetic field mitigation using an electromagnetic shielding technique. *International Journal of Occupational Safety and Ergonomics*, 2021, vol. 28, no. 3, pp. 1672-1682. doi: 10.1080/10803548.2021.1918923

[3] Kheifets L., Crespi C. M., Hooper C., Cockburn M., Amoon A. T., Vergara X.P. Residential magnetic fields exposure and childhood leukemia: a population-based case–control study in California. *Cancer Causes & Control*, 2017, vol. 28, no. 10, pp. 1117-1123. doi: 10.1007/s10552-017-0951-6

[4] Focke F., Schuermann D., Kuster N., Schär P. DNA fragmentation in human fibroblasts under extremely low frequency electromagnetic field exposure. *Mutation Research/Fundamental and Molecular Mechanisms of Mutagenesis*, 2010, vol. 683, no. 1-2, pp. 74-83. doi: 10.1016/j.mrfmmm.2009.10.012

[5] *Exposure limits for low-frequency fields (public). World Health Organization*. Available online: http://apps.who.int/gho/data/node.main.EMFLIMITSPUBLICLOW?lang=en

[6] Krasnozhon A.V., Buinyi R.O., Dihtyaruk I.V., Kvytsynskyi A.O. The investigation of distribution of the magnetic flux density of operating two-circuit power line 110 kV «ChTPP-Chernihiv-330» in the residential area and methods of its decreasing to a safe level. *Electrical engineering & Electromechanics*, 2020, no. 6, pp. 55-62. doi: 10.20998/2074-272X.2020.6.08

[7] Rozov V.Yu., Reutskyi S.Yu., Pelevin D.Ye., Pyliugina O.Yu. The magnetic field of power transmission lines and the methods of its mitigation to a safe level. *Technical Electrodynamics*, 2013, no. 2, pp. 3-9.

[8] Moro F., Turri R. Fast analytical computation of power-line magnetic fields by complex vector method. *IEEE Transactions on Power Delivery*, 2008, vol. 23, no. 2, pp. 1042-1048. doi: 10.1109/TPWRD.2007.915212.

[9] Gallego-Martínez R., Muñoz-Gutierrez F.J., Rodríguez-Gómez A. Trajectory optimization for exposure to minimal electromagnetic pollution using genetic algorithms approach: A case study. *Expert Systems With Applications*, 2022, vol. 207, paper 118088. doi: 10.1016/j.eswa.2022.118088

[10] Satayev M.I., Azimov A.M., Faiz N.S., Berdaliyeva A.A., Satayeva Z.I., Nikonov O.Y. Assessment of the impact of electromagnetic radiation in low-frequency energy facilities on the residential ecological zone. *GEOMATE Journal*, 2021, vol. 21, no. 83, pp. 132-141. doi: 10.21660/2021.83.j2100

[11] Al-Bassam E., Elumalai A., Khan A., Al-Awadi L. Assessment of electromagnetic field levels from surrounding high-tension overhead power lines for proposed land use. *Environmental Monitoring and Assessment*, 2016, vol. 188, pp. 1-12. doi: 10.1007/s10661-016-5318-z

[12] Mimos E.I., Tsanakas D.K., Tzinevrakis A.E. Optimum phase configurations for the minimization of the magnetic fields of underground cables. *Electrical Engineering*, 2010, vol. 91, pp. 327-335. doi: 10.1007/s00202-009-0126-x.

[13] Mahdipour M., Akbari A., Khalilzadeh M., Werle P. Impact of different bonding methods on high voltage cable shield induced voltage and current in normal and fault conditions. *Proceedings of the 2017 Iranian Conference on Electrical Engineering*, pp. 1308-1312. doi: 10.1109/IranianCEE.2017.7985244

[14] Lunca E., Vornicu S., Salceanu A. Numerical modelling of the magnetic fields generated by underground power cables with two-point bonded shields. *Proceedings of the 25th IMEKO TC-4 International Symposium on Measurement of Electrical Quantities*, 2022, pp. 221-226.

[15] Lin Y., Xu Z. Cable sheath loss reduction strategy research based on the coupled line model. *IEEE Transactions on Power Delivery*, 2015, vol. 30, no. 5, pp. 2303-2311. doi: 10.1109/TPWRD.2015.2414655

[16] *State Standard SOU-N MEV 40.1-37471933-49:2011. Design of cable lines with rated voltage up to 330 kV. Guidance*. Kyiv, Minenergovugillya of Ukraine Publ., 2017, 139 p. (In Ukrainian)

[17] Cardelli E., Faba A., Pirani A. Nonferromagnetic open shields at industrial frequency rate. *IEEE Transactions on Magnetics*, 2010, vol. 46, no. 3, pp. 889-898. doi: 10.1109/TMAG.2009.2031110

[18] Ippolito M.G., Puccio A., Ala G., Ganci S. Attenuation of low frequency magnetic fields produced by HV underground power cables. *Proceedings of the 2015 50th International Universities Power Engineering Conference*, pp. 1-5. doi: 10.1109/UPEC.2015.7339774

[19] del-Pino-López J.C., Cruz-Romero P., Serrano-Iribarnegaray L., Martínez-Román J. Magnetic field shielding optimization in underground power cable duct banks. *Electric Power Systems Research*, 2014, vol. 114, pp. 21-27. doi: 10.1016/j.epsr.2014.04.001

[20] De Wulf M., Wouters P., Sergeant P., Dupre´ L., Hoferlin E., Jacobs S., Harlet P. Electromagnetic shielding of high-voltage cables. *Journal of Magnetism and Magnetic Materials*, 2007, no. 316, pp. 908-911. doi: 10.1016/j.jmmm.2007.03.137

[21] Sergeant P., Koroglu S. Electromagnetic losses in magnetic shields for buried high voltage cables. *Progress in Electromagnetics Research*, 2011, vol. 115, pp. 441-460. doi: 10.2528/PIER11022206

[22] Zucca M., Lorusso G., Fiorillo F., Roccato P.E., Annibale M. Highly efficient shielding of high-voltage underground power lines by pure iron screens. *Journal of Magnetism and Magnetic Materials*, 2008, vol. 320, no. 20, pp. 1065-1069. doi: 10.1016/j.jmmm.2008.04.096

[23] Rozov V.Yu., Grinchenko V.S., Yerisov A.V., Dobrodeyev P.N. Efficient shielding of three-phase cable line magnetic field by passive loop under limited thermal effect on power cables. *Electrical Engineering & Electromechanics*, 2019, no. 6, pp. 50-54. doi: 10.20998/2074-272X.2019.6.07

[24] Canova A., Bavastro D., Freschi F., Giaccone L., Repetto M. Magnetic shielding solutions for the junction zone of high voltage underground power lines. *Electric Power Systems Research*, 2012, vol. 89, pp. 109-115. doi: 10.1016/j.epsr.2012.03.003

[25] del-Pino-López J.C., Cruz-Romero P. The effectiveness of compensated passive loops for mitigating underground power cable magnetic fields. *IEEE Transactions on Power Delivery*, 2011, vol. 26, no. 2, pp. 674-683. doi: 10.1109/TPWRD.2009.2039150

[26] Maioli P., Zaccone E. Thermal design of HV electric systems with EMF mitigation devices. *Proceedings of the International Colloquium Power Frequency Electromagnetic Fields*, 2009, paper R.18.

[27] Maioli P., Zaccone E. Passive loops technique for electromagnetic fields mitigation: applications and theoretical considerations. *Proceedings of the Jicable International Conference on Insulated Power Cables*, 2007, pp. 231-236.

[28] Canova A., Giaccone L. Magnetic mitigation of HV cable junction zone. *Proceedings of the 8th International Conference on Insulated Power Cables*, 2011, paper B.1.6.

[29] Frezzi P., Hug R., Grant J., Klingler A. Passive magnetic field compensation of existing underground cables. *Proceedings of the 2016 International Symposium on Electromagnetic Compatibility*, pp. 876-881. doi: 10.1109/EMCEurope.2016.7739246

[30] *Electric cables – Calculation of the current rating – Part 1-1: Current rating equations (100 % load factor) and calculation of losses – General*, IEC 60287-1-1, 2014.

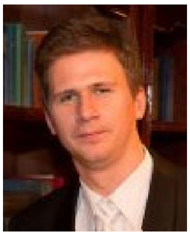
[31] *Electric cables – Calculation of the current rating – Part 2-1: Thermal resistance – Calculation of thermal resistance*, IEC 60287-2-1, 2015.

[32] Gouda O.E. *Environmental Impacts on Underground Power Distribution*, 1st edition, IGI Global, 2016, 405 p.

[33] 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

[34] 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

Information about authors.



Volodymyr Grinchenko, Ph.D., Senior Researcher. Department for Energy Efficiency and Energy Balances Forecasting of General Energy Institute of National Academy of Sciences of Ukraine. Field of scientific interests includes electromagnetic and magnetic passive shielding, active shielding, non-linear effects in electrical engineering problems, and heat transfer applications.
E-mail: vsgrinchenko@gmail.com

Oleksandr Tkachenko, Ph.D., Researcher. Department of Magnetism of Technical Objects of Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine. Current research and scientific interests are related to the study of cable lines control and computer simulation of physical processes in power systems.
E-mail: oleksandr.tk7@gmail.com