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Approximate method for calculating the magnetic field of 330-750 kV high-voltage power line in maintenance area under voltage

Problem. *In order to organize effective protection of working personnel from the action of strong electromagnetic influence when performing work on live high-voltage power lines (HVPL), the existing methods of calculating the magnetic field (MF) need to be developed in the direction of their simplification during operational use.* ***Goal***. *The purpose of the work is to develop an approximate method and a simplified methodology for calculating the magnetic field flux density near the surface of the 330-750 kV HVPL wires for the prompt determination of the safe distance of the working personnel to the surface of the HVPL wires at the current value of their operating current.* ***Methodology***. *A new approximate method of calculating the flux density of the MF in the area of work on live HVPL based on the Biot-Savart law and determining the maximum values of the flux density of the MF on the axes of symmetry N of the suspension of N wires, which are decisive for the protection of working personnel, is proposed.* ***Results***. *Exceeding the maximum acceptable level of the MF for individual power lines at their nominal currents, adopted in the European Union, and the need to implement measures to reduce MF were revealed.* ***Originality***. *It is shown that the distribution of the 330-750 kV HVPL near N of its split wires with an error of no more than 2.5 % can be determined by the current of only one of the phases of the HVPL. This distribution of MF, which is uneven, is determined by the order of axial symmetry N with the maximum values of the flux density of the MF lying on the axes of symmetry N of the suspension of the phase wires.* ***Practical value.*** *The development of an approximate method and a simplified methodology for calculating the flux density of the MF near the surface of the wires of 330-750 kV HVPL, which allows you to quickly, without the use of a computer, calculate the safe distance to the wires of a specific HVPL at the current value of its operating current, as well as determine the necessary measures for the protection of personnel from the MF, which can be implemented either by physically limiting the minimum distance from the worker's body to the surface of the wires to a dangerous one, or by necessary reduction of the HVPL operating current during repair work.* ***Verification.*** *An experimental verification of the proposed method and methodology was carried out on a laboratory installation with a mock-up of a phase of a 330 kV HVPL from AC 400 type* wires *at 1500 A current, which confirmed the correctness of the proposed calculation relationships.* References 30, figures 9.

Key words: **high-voltage power line, live-line maintenance, magnetic field near wires, calculation method**.

Проблема. *Для організації ефективного захисту робочого персоналу від дії сильного електромагнітного впливу при виконанні робіт на високовольтних лініях електропередачі (ЛЕП) під напругою, потребують розвитку існуючі методи розрахунку магнітного поля (МП) в напрямі їх спрощення при оперативному використанні.* ***Мета.*** *Метою роботи є розробка наближеного методу та спрощеної методики розрахунку індукції магнітного поля поблизу поверхні проводів ЛЕП 330-750 кВ для оперативного визначення безпечної дистанції робочого персоналу до поверхні проводів ЛЕП при поточному значенні їх робочого струму.* ***Методологія.*** *Запропоновано новий наближений метод розрахунку індукції МП в зоні виконання робіт на ЛЕП під напругою, що ґрунтується на законі Біо-Савара, та визначенні максимальних значень індукції МП ЛЕП на осях симетрії N підвісу N проводів, що є визначальними для захисту робочого персоналу.* ***Результати.*** *Виявлено перевищення прийнятого в Євросоюзі гранично допустимого рівня МП для окремих ЛЕП при їх номінальних струмах, та необхідність реалізації заходів із зменшення МП.* ***Оригінальність.*** *Показано, що розподіл МП ЛЕП 330-750 кВ поблизу N її розщеплених проводів з похибкою не більш 2,5 % може визначатися за МП тільки однієї із фаз ЛЕП. Цей розподіл МП, що є нерівномірним, визначається порядком осьової симетрії N з максимальними значеннями індукції магнітного поля, що лежать на осях симетрії N підвісу проводів фаз.* ***Практична цінність.*** *Виконана розробка наближеного методу і спрощеної методики розрахунку індукції магнітного поля поблизу поверхні проводів високовольтної ЛЕП 330-750 кВ, що дозволяють оперативно, без використання комп'ютера, розраховувати безпечну відстань до проводів конкретної ЛЕП при поточному значенні її робочого струму, а також визначати необхідні заходи із захисту персоналу від МП, які можуть бути реалізовані або шляхом фізичного обмеження мінімальної відстані від тіла робітника до поверхні проводів до небезпечної, або необхідного зменшення робочого струму ЛЕП на час ремонтних робіт.* ***Верифікація.*** *Здійснено експериментальну перевірку запропонованих метода та методики на лабораторній установці з макетом фази ЛЕП 330 кВ із проводів типу АС 400 при струмі 1500 А, яка підтвердила коректність запропонованих розрахункових співвідношень.* Бібл. 30, рис. 9.

Ключові слова: **високовольтна лінія електропередачі, роботи без зняття напруги, магнітне поле поблизу проводів, метод розрахунку.**

Introduction. One of the effective ways of increasing the profitability of main power networks is to carry out the repair work on overhead power lines (PLs) of ultra-high voltage under working voltage [1-6]. This allows to preserve the power supply of consumers during the repair period. However, when organizing such works, which are carried out in Ukraine by the staff of the National Energy Company NPC Ukrenergo near power lines (Fig. 1), there is a problem of protecting personnel from the action of a strong electromagnetic field of power frequency, which is characterized by the current values of the strength E of the electric field (EF) and the flux density B of the magnetic field (MF) and can reach a dangerous level [7, 8].

At present, the problem of personnel protection from the EF is practically solved with the help of special shielding protective suits (Fig. 1) made of electrically conductive material [9-13]. But these suits do not shield the MF [14, 15]. The known methods for passive and active shielding of the PL's MF used to reduce it in residential and public buildings [16-20] also cannot be applied near PLs' wires, as they require a significant amount of free space for placing shielding elements,

Fig. 1. Execution of repair works by NPC «Ukrenergo» on the 330 kV power line under voltage

which is not near PL's wires. Therefore, the protection of personnel from the PL's MF near its wires, which is potential [21, 22] and decreases when moving away from the PL, can be carried out in the traditional way – distance protection [19] by introducing a safe distance between the wires and the worker's body. Such distance should ensure that the flux density of the MF on the worker's body falls to the maximum permissible level (6 mT), which is regulated by the requirements of the European Union [7, 8]. To determine this safe distance, it is necessary to quickly, in the field, after receiving data on the current load of the PL, perform calculations of the flux density of the MF in the working area of the PL (Fig. 1). The working zone is formed at a distance of 2 mm to *L* mm from the surface of the PL's wires. Here, 2 mm is the thickness of the protective suit, which limits the minimum distance between the wire and the worker's body when he/she touches the wire, and *L* is the safe distance at which the flux density of the PL's MF is guaranteed to fall to the maximum permissible level.

However, the known methods of calculating MF, near PL's wires [23-27], are based on numerical calculations that are quite difficult for the practical use and require the use of the computer special code. This makes it difficult to perform an operational determination in the field of the flux density of the MF near the PL's wire, which is necessary for the organization of safe work of personnel from point of view of the MF when performing repair work on the PL under load under voltage. Analytical methods based on Biot-Savart law [21, 22, 28] are more acceptable for operational calculation of the MF of the PL. But these methods are justified only for calculating the MF at a significant distance from the PL, which exceeds the interphase distance between its wires [21, 22, 29]. In addition, the specified methods do not take into account such a feature of the design of the phase wires of the 330-750 kV PL's wires as their splitting, which is essential for the calculation of the MF [2, 3, 30] and also require the use of a computer. Thus, the known methods of calculating MF near 330-750 kV PL's wires need to be developed.

The goal of the work is to develop an approximate method and a simplified technique for calculating the flux density of the magnetic field near the surface of 330-750 kV PL's wires for operational determination of the safe distance of working personnel to the surface of PL's wires at the current value of their operating current.

Design of 330-750 kV power lines. The analysis of the geometric dimensions of the suspension of wires of real 330-750 kV PLs [2, 30] shows that their phases are performed by split into $N \in$ (2-5) wires, the axes of which lie at the vertices of regular symmetrical polygons (Fig. 2) with the radius of the circumscribed circle *R*.

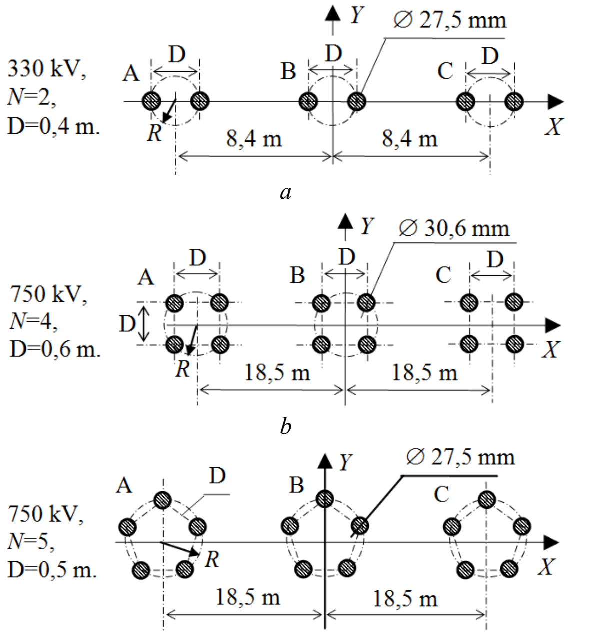

Fig. 2. Design of the suspension of the wires of the 330-750 kV PLs working in Ukraine

As follows from Fig. 2, diameters *d* of the PL's wires of 27-31 mm is an order of magnitude smaller than the distance *D* of 0.4-0.6 m between split phase wires and the interphase distance of 8.4-18.5 m. This makes it possible to ignore the non-uniformity of the current density in the wires caused by the proximity effect when calculating the MF, and to successfully use the analytical method [22] for the approximate calculation of the MF's flux density of the PL at observation points *P* (Fig. 3), which are located near the surface of the wires ($l_r \in$ (0.002-500 mm).

Method of calculation of the MF. We substantiate the possibility of performing the calculation of the flux density of the MF when placing the observation point *P* (Fig. 3) near the surface of the PL's wires, based on the use of the method proposed by the authors in [22, 29], which is based on the Biot-Savart law and has undergone thorough experimental verification.

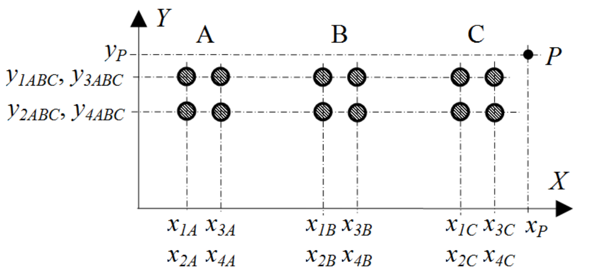

Fig. 3. Coordinates of the location of the wires of the PL's phases and observation point *P* on the example of a 750 kV PL

We perform the analysis on a plane oriented normal to the direction of the PL's axis direction for the suspension of wires in accordance with Fig. 4 with typical assumptions [21, 22] about potentiality and plane-parallelism of the PL's MF. These assumptions must be supplemented with the provisions that the currents in the split wires of the individual phases of the PL are identical, have a uniform density, and the wires are made of a homogeneous material and have the correct right shape with diameter d.

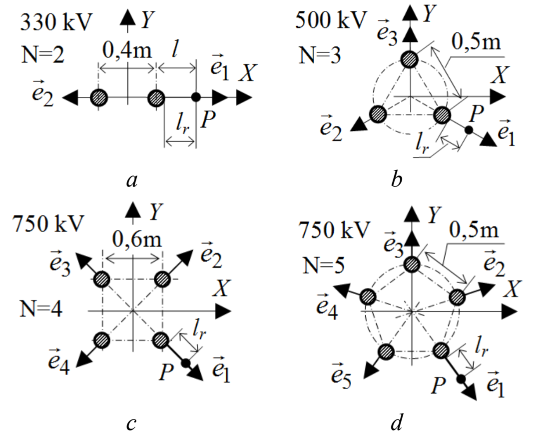

Fig. 4. Geometry of the suspension of the phase wires of the 330-750 kV PLs

Then, according to [22, 29], the effective values of the components of the MF's flux density vector of each phase $\xi \in A,B,C$ at the observation point P (Fig. 3) when the phases of the power line are split into N wires can be calculated as:

$$B_{x,\xi,n}(P)=\frac{\mu_0}{2\pi}\frac{I}{N}\sum_{n=1}^{N}\frac{y_P-y_{\xi,n}}{\left(x_P-x_{\xi,n}\right)^2+\left(y_P-y_{\xi,n}\right)^2}, \quad (1)$$

$$B_{y,\xi,n}(P)=-\frac{\mu_0}{2\pi}\frac{I}{N}\sum_{n=1}^{N}\frac{x_P-x_{\xi,n}}{\left(x_P-x_{\xi,n}\right)^2+\left(y_P-y_{\xi,n}\right)^2}, \quad (2)$$

$$B_d(P)=\sqrt{\left(B_x(P)\right)^2+\left(B_y(P)\right)^2}, \quad (3)$$

where I is the phase current of the PL; x_P, y_P are the coordinates of the observation point P; $x_{\xi,n}$, $y_{\xi,n}$ are the coordinates of the intersection of the axes of the wires of n phases $\xi \in A,B,C$ of the plane, perpendicular to the axis of the PL, $B_d(P)$ is the module of the MF's flux density vector at the point P.

The results of the calculation of the magnetic flux density distribution of phase A of the PL according to (1)-(3) at different N (Fig. 2) and nominal current are presented in Fig. 5. The distribution of the MF for other phases of the PL is identical.

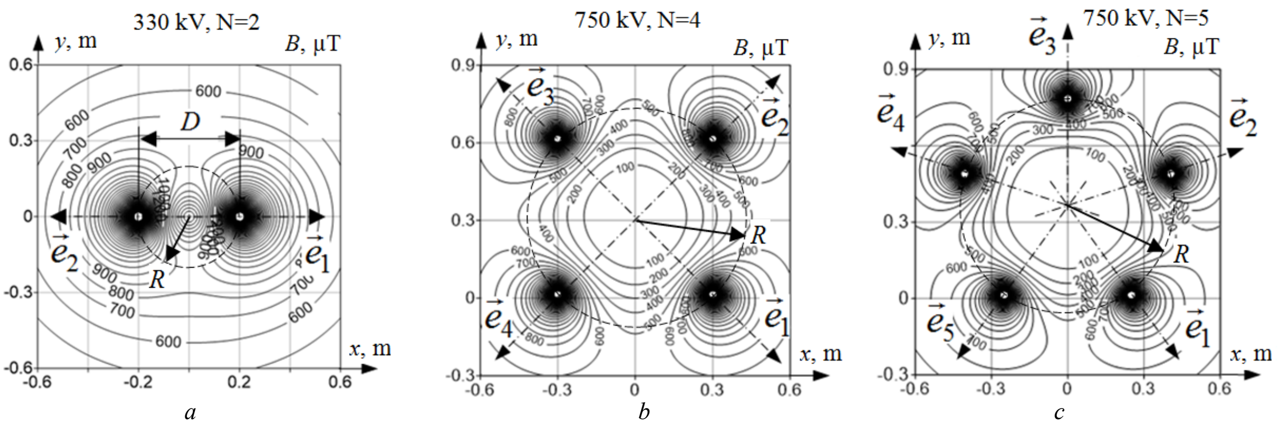

Fig. 5. Distribution of the MF's flux density near phase wires of different PLs in a plane normal to its axis

The analysis of the nature of the distribution of the MF's flux density (Fig. 5) shows that it is irregular and has zones with maximum values that coincide with the directions $\vec{e}$ (Fig. 4, 5), which are determined by the order of axial symmetry of N wires of the PL's phase. Therefore, it is proposed to calculate the MF on the axes of symmetry under the conditions $P \in \vec{e}$, which correspond to the worst cases for the working personnel with the maximum values of the MF's flux density and at the same time make it possible to significantly simplify the calculation.

Figure 6 presents the results of the calculation according to (1)-(3) of the flux density of the MF phases of different PLs at nominal currents and remote observation points from the surface of the wires by distance l_r. As follows from Fig. 6, at nominal currents, the flux density of the MF at the minimum distance from P to the wires (2 mm) ranges from 11.4 mT for 330 kV PL to 6.4 mT for 750 kV PL and exceeds the maximum permissible level of 6 mT in 1.9-1 .07 times.

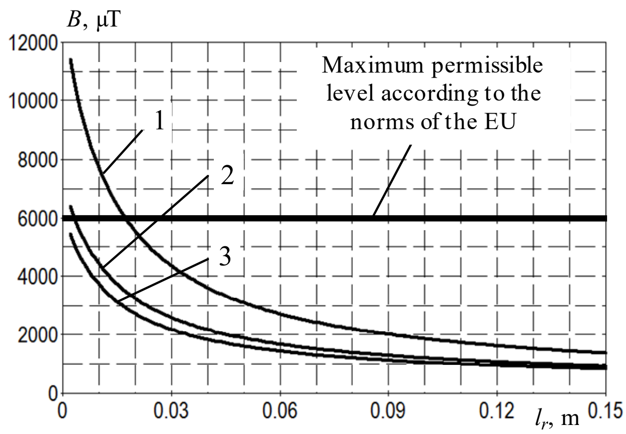

Fig. 6. Dependence of maximum values of the MF's flux density of different PLs on the distance l_r to the surface of their wires (1 – PL 330, N=2, I_n=1.7 kA; 2 – PL 750, N=4, I_n=2 kA; 3 – PL 750, N=5, I_n=2 kA)

For the worst case (for 330 kV PL, Fig. 2,*a*), the flux density of the MF drops to the maximum permissible level only at l_r = 17 mm, which indicates the need to limit the working distance by 15 mm, or to reduce the load of the PL and its operating current accordingly to 0.52 from the nominal. Here, the working zone L of the PL in the calculation can be limited to a distance of l_r = 20 mm, at which the mutual influence of the MF from the currents of different phases of the PL can be neglected. Then the calculation of the maximum values of the flux density of the MF near the PL's wires can be performed for one phase and according to (1)-(3) will be described by the following relationships:

$$P \in \vec{e}, \sqrt{(x_P - x_n)^2 + (y_P - y_n)^2} > R, \tag{4}$$

$$B_{\max x,n}(P) = \frac{\mu_0}{2\pi}\frac{I}{N}\sum_{n=1}^{N}\frac{y_P - y_n}{(x_P - x_n)^2 + (y_P - y_n)^2}, \tag{5}$$

$$B_{\max y,n}(P) = -\frac{\mu_0}{2\pi}\frac{I}{N}\sum_{n=1}^{N}\frac{x_P - x_n}{(x_P - x_n)^2 + (y_P - y_n)^2}, \tag{6}$$

$$B_{\max d}(P) = \sqrt{(B_{\max x}(P))^2 + (B_{\max y}(P))^2}, \tag{7}$$

where $\vec{e}$ is the vector the direction of which coincides with one of the N axes of symmetry of split PL's wires.

Here, the relative error of the calculation when using (4)-(7), which do not take into account the mutual influence of the MF from the currents of different phases of the PL compared to the calculation based on (1)-(3), does not exceed 2.5 % (Fig. 7) and is quite acceptable for approximate calculation.

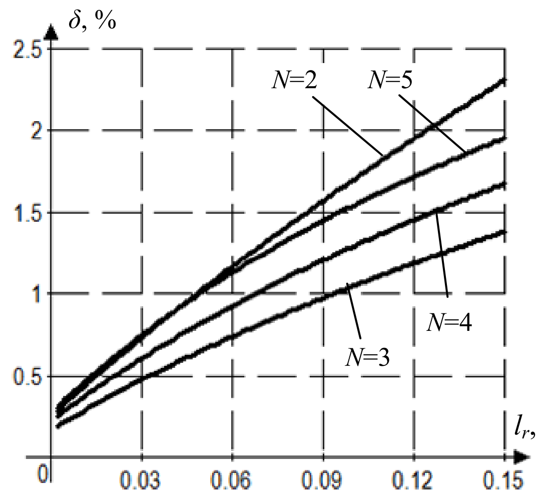

Fig. 7. Calculated by (4)-(7) and (1)-(3) the relative error of calculation of the MF of different PLs near wires of one phase without taking into account the influence of the MF from currents of other phases ($N \in$ 2-5)

To further simplify the calculation, we transform the ratios (4)-(7), moving from the coordinates of the location of the wires x_P, y_P, x_n, y_n to the geometric parameters of the suspension of the wires R, D and the distance l (Fig. 2-4) and obtain the following simplified calculation relations for different N:

$$B_{N=2}(l) = I \cdot \frac{\mu_0}{2\pi}\frac{(l+R)}{l(l+2R)}, \tag{8}$$

$$B_{N=3}(l) = I \cdot \frac{\mu_0}{6\pi}\left[\frac{1}{l} + \frac{2(l+1.5R)}{l^2 + 3Rl + 3R^2}\right], \tag{9}$$

$$B_{N=4}(l) = I \cdot \frac{\mu_0}{2\pi}\frac{(l+R)^3}{(l+R)^4 - R^4}, \tag{10}$$

$$B_{N=5}(l) = I \cdot \frac{\mu_0}{10\pi}\left[\frac{1}{l} + \frac{2(l+R-R\cos(2\pi/5))}{(l+R-R\cos(2\pi/5))^2 + (R\sin(2\pi/5))^2} + \frac{2(l+R-R\cos(4\pi/5))}{(l+R-R\cos(4\pi/5))^2 + (R\sin(4\pi/5))^2}\right], \tag{11}$$

where $R = \dfrac{D}{2\sin(\pi/N)}$; l is the distance from the axis of the wire to the point of observation P.

The obtained calculation relationships (4)-(11) are the scientific basis for a simplified calculation method and allow to quickly, with the help of a calculator, calculate the maximum values of the magnetic flux density of the PL for the current values of the load current as a function of the distance l to the PL's wires, taking into account the geometry of their suspension.

Thus, on the basis of the above analysis, an approximate calculation method (4)-(7) and a simplified calculation technique (8)-(11) built on its basis can be proposed for the operational determination of the flux density of the MF in the area of performance of works on live PL, which is based on the Biot-Savart law and determining the maximum values of flux density for any of the phases lying on the axes of symmetry of the suspension of the split wires and determining the safe distance to the wires of a specific PL at the current value of its operating current.

The use of the proposed method and technique allows to quickly determine specific measures to protect personnel from the MF when performing work under voltage, which can be implemented either by limiting the minimum distance from the worker's body to the wires (installation of capes or mats of the required thickness on the PL's wires in the working area), or a corresponding reduction in the operating current of the PL for the period of repair works.

Experimental verification of the proposed method and calculation technique. The experimental verification of the proposed calculation relationships (8)-(12) was carried out on an experimental installation with a laboratory model of a phase of the 330 kV PL (Fig. 8), which was created at the magnetomeasuring stand of the magnetodynamic complex of the Department of Magnetism of Technical Objects of the Institute of A.M. Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine.

The model is made on the basis of 2 PL's wires of AC 400 type with d = 28 mm and length of 5 m and their arrangement according to Fig. 2,*a*. The experimental installation allows to carry out research with current in each wire from 100 to 750 A (200-1500 A per phase). A three-phase induction regulator of the IR62 type

(P_n = 30 kVA, U_n = 22-382 V), loaded on two step-down single-phase transformers of the OSU-80/0.5 type (P_n =100 kVA, U_n = 12.2 V, I_n = 8140 A), which are connected to the corresponding wires of the laboratory installation, was used as a regulated power source. The MF's flux density was measured by a Gaussmeter 410 type magnetometer with a special sensor positioning system (Fig. 8), and the current in the model wires was measured using TNFP3000/5 A type current transformers and E526 type ammeters.

Fig. 8. Experimental installation with a laboratory model of a 330 kV PL's phase and a magnetometer sensor positioning device

The results of the experimental studies are presented in Fig. 9 and confirm the coincidence of the results of the calculation and the experiment at nominal current in the wires of 500-750 A with a spread of no more than 10 %, which is quite acceptable for a physical experiment.

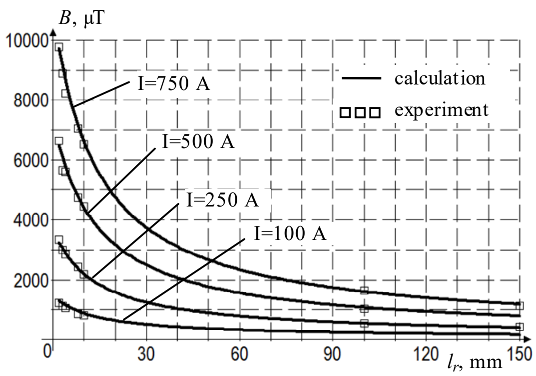

Fig. 9. Results of measuring the flux density of the MF on the laboratory model of the phase of the PL 330 (Fig. 8) at l_r = 0.002-0.150 m and currents in wires of 100-750 A and their comparison with the calculation

This spread is mainly related to the imperfection of the AC 400 type wire (it is made of twisted cores, see Fig. 8) and requires further analysis. When the current decreases, the error increases which is associated with an increase in the influence of interference from the power supply cables of the model (Fig. 8).

Conclusions.

1. An analysis of the geometric dimensions of the suspension of wires of typical 330-750 kV PLs was performed, based on which it was shown that for the approximate calculation of the magnetic flux density near their wires, an analytical method based on the Biot-Savart law can be used with the determination of the magnetic field only for one of its phases, without taking into account the influence of the magnetic field of the currents of other phases, which allows to simplify the calculation with a limited error not exceeding 2.5 %.
2. The calculation of the magnetic flux density near the wires of operating overhead power lines 330-750 kV was carried out at their nominal currents, which showed an excess of the maximum permissible magnetic flux density level adopted in the European Union (6 mT) for 330 kV power lines with N=2 (at distance from the surface of the wires of 17 mm) and 750 kV with N=4 (at distance of 3 mm) and the need to take measures to reduce the magnetic field acting on personnel when performing live work.
3. An approximate method of calculating the magnetic flux density near the surface of N the split wires of the phases of the 330-750 kV power lines, the axes of which lie at the vertices of symmetric polygons with the order of symmetry N, is proposed, which is based on determining only the maximum values of the magnetic flux density lying on the axes of symmetry of N suspension of wires and are decisive for the organization of protection of working personnel from the action of the magnetic field. The method allows to significantly simplify the calculation, performing it only for the axes of symmetry, and not for the entire space.
4. On the basis of the proposed approximate method, a simplified technique of calculating the magnetic field has been developed, which can be implemented without the use of a computer, which allows in the field to quickly calculate the safe distance to the wires of the specific power line at the current value of its operating current and to determine the measures necessary to protect personnel from the MF when performing live work, which can be implemented either by physically limiting the distance from the worker's body to the surface of the wires to a dangerous distance, or by necessary reducing the operating current of the power line during repair work.
5. Experimental verification of the proposed approximate method and the simplified technique of calculating the magnetic field based on it was carried out on a laboratory installation with a phase model of a 330 kV power line made of wires of the AC 400 type at nominal current of 1500 A (750 A per wire). The experiment confirmed the coincidence of the results of the calculation and the experiment with an acceptable error for engineering calculations of no more than 10 %, and the correctness of the proposed calculation method, as well as the feasibility of developing on their basis

normative documents of the Ministry of Energy of Ukraine on the protection of working personnel from the negative impact of the magnetic field when performing work on power transmission lines under voltage.

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Conflict of interest. The authors declare no conflict of interest.

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