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Protection of workers against the magnetic field of 330-750 kV overhead power lines when performing work without removing the voltage under load

Problem. *One of the acute problems that needs to be solved when performing repair work under voltage on power transmission lines (PTLs) is the protection of workers' health from high-intensity electromagnetic fields.* ***Goal****. The purpose of the work is to develop the methodological foundations for the protection of workers from the magnetic field (MF) of the 330-750 kV PTL during repairing work without removing the voltage and under loading.* ***Methodology.*** *A methodology for calculating the maximum allowable PTL loading factor has been developed. It limits the flux density of the MF in the working area of the power transmission line to the maximum permissible level of sanitary standards for the given period of work at the potential and the minimum thickness of the protective layer between the wires and the worker's body.* ***Originality****. Methodological principles for protecting workers from magnetic fields have been created. They are based on the joint use of the developed method of mode load minimization and the method of increasing the working distance, and the developed method of calculating the maximum allowable loading factor of PTLs.* ***Practical value****. The graphic dependence of the maximum allowable loading factor of the PTL is proposed as a function of the required working time and the thickness of the introduced additional protective layer between the wires and the body of the worker. It allows one quickly determines the maximum allowable loading factors to conform the accepted limit-allowable normative level of flux density of MF for various types of PTLs 330-750 kV.* References 45, tables 1, figures 10.
Key words: **high-voltage power line, work on wires without removing the voltage, reducing the magnetic field.**

Проблема. *Однією із гострих проблем, що потребує вирішення при виконанні ремонтних робіт під напругою на лініях електропередачі (ЛЕП), є захист здоров'я працівників від електромагнітного поля високої інтенсивності.* ***Мета.*** *Метою роботи є розроблення методологічних основ захисту працівників від магнітного поля (МП) ЛЕП 330-750 кВ при виконанні ремонтних робіт без зняття напруги і під навантаженням.* ***Методика****. Розроблено методику розрахунку гранично допустимого коефіцієнту навантаження ЛЕП, який обмежує індукцію МП в робочій зоні ЛЕП до гранично допустимого рівня санітарних норм при заданих терміні робіт на потенціалі і мінімальній товщині захисного слою між проводами та тілом працівника.* ***Наукова новизна****. Створені методологічні засади захисту працівників від МП, що ґрунтуються на сумісному використанні розроблених методу режимної мінімізації навантаження і методу збільшення робочої дистанції, та розробленої методики розрахунку гранично допустимого коефіцієнту навантаження ЛЕП.* ***Практична значимість*** *Запропоновані графічні залежності гранично допустимого коефіцієнту навантаження ЛЕП в функції від необхідного часу роботи та товщини введеного додаткового захисного слою між проводами та тілом працівника, що при прийнятому гранично допустимому нормативному рівні індукції МП дозволяє оперативно визначати гранично допустимі коефіцієнти навантаження для різних типів ЛЕП 330-750 кВ.* Бібл. 45, табл. 1, рис. 10.
Ключові слова: **високовольтна лінія електропередачі, роботи без зняття напруги, зменшення магнітного поля.**

Introduction. Carrying out repair work on high-voltage overhead power transmission lines (PTLs) without de-energizing is a common method of increasing their profitability [1-4]. One of the acute problems that needs to be solved when performing such works is the protection of workers' health from the electromagnetic field (EMF) of power frequency PTLs with increased intensity [5-8]. Such EMF can be characterized by independent components – electric field (EF) and magnetic field (MF) [9, 10], each of which negatively affects human health [11, 12]. Therefore, in the leading countries of the world, methods of replacing workers with robotic devices when performing work on the potential of PTLs are currently developing rapidly [13-15].

In Ukraine, workers have been working on the potential of high-voltage PTLs for more than 40 years, and their technology is constantly being improved [1-4]. To date, the problem of protecting the health of working personnel from the negative effects of PTLs' EF, based on the use of special protective suits made of electrically conductive material, has been solved [4]. But the solution of the problem of protecting workers from the action of the MF is in a significantly worse state. This problem remains insufficiently developed both theoretically and practically. Therefore, a certain step in its solution was the development by the authors of a mathematical model of the MF in the area of work without removing the voltage under the load [16], and the methodology for its calculation, which are based on the results of previously performed studies of the MF of various technical objects [17-31]. The latest research by the authors [16] confirms the relevance of solving the problem of protecting workers from the effects of the MF in Ukraine when performing work on PTLs without de-energizing. For example, in [16] it is shown that for typical 330-750 kV PTLs, in the nominal mode of their operation, it is possible to significantly exceed the upper limit level of MF flux density by 1.5-1.9 times over the norms adopted in Ukraine and the European Union [12, 32-34]. Therefore, the task of creating scientific principles for the protection of working personnel from the action of the MF by reducing it to a safe level in the PTL wires execution zone is urgent.

The goal of the work is to develop methodological principles for the protection of workers from the magnetic field of the 330-750 kV PTLs when carrying out repair work without removing the voltage and under load.

Normalization of the limit level of the MF action with frequency of 50 Hz. In Ukraine, the limit level of action (LLA) of the MF flux density on PTL workers is regulated in [33] and summarized in item 1 of Table 1. For example, for the body of a worker, the LLA is no more than 7.5 mT when working for up to 1 hour and no more than 1.8 mT when working for 8 hours. In the interval between one and eight hours, the MF LLA B_{PD} in [33, 34] is determined as a function of time according to the methodology developed on the basis of sanitary-hygienic and biological research carried out in the institutes of the National Academy of Medical Sciences of Ukraine [35-37]. For the limbs of the worker, the MF LLA is much larger and amounts to 15 mT (item 1, Table 1).

In Europe, in accordance with the Directives of the European Union [12], the MF LLA for workers is stricter. Thus, the upper level of LLA for the body is 6 mT (with short-term exposure), and the lower one is 1 mT (with long-term exposure). To date, this standard [12] has been approved in Ukraine [32] and it is expected to be put into effect after the termination or abolition of martial law in Ukraine. Therefore, we will consider this European Standard to be promising.

Taking into account the above, in the further analysis we will use the «State sanitary rules and regulations for the performance of work in non-switched-off electrical installations with voltage of up to 750 kV inclusive» (item 1, Table 1) in force in Ukraine as the standard for the 50 Hz MF LLA in the further analysis, and for comparison – the Directives of the European Union [32], which are promising for Ukraine, approved by the order of the Ministry of Health No. 81 dated 13.01.2023.

Table 1

LLA of the flux density B_{PD} of the sinusoidal MF with frequency of 50 Hz per worker

No.	Normative document	Work time of the worker (t_r) at the PTL potential (hours)							
		≤1	2	3	4	5	6	7	≥8
		LLA of the flux density B_{PD} when affecting the body/limbs, mT							
1	**Current regulatory document:** Order of the Ministry of Health of Ukraine dated 09.07.1997 No. 198 «State sanitary rules and regulations for the performance of work in non-switched-off electrical installations with voltage up to and including 750 kV»	7,5/ 15,0	6,1/ 15,0	5,0/ 15,0	4,0/ 15,0	3,1/ 15,0	2,5/ 15,0	2,0/ 15,0	1,8/ 15,0
2	**Prospective maximum permissible levels of MF action** based on Directives 89/391/EEC and Order of the Ministry of Health dated 13.01.2023 No. 81 «Minimum requirements for health and safety of workers exposed to electromagnetic fields», supplemented by marked with * B_{PD} values, according to the method used in Ukraine	6,00/ 18,00	4,65*/ 18,00	3,60*/ 18,00	2,78*/ 18,00	2,15*/ 18,00	1,67*/ 18,00	1,29*/ 18,00	1,00/ 18,00

The working distance between the wires and the worker's body and the working MF flux density. When performing work on the PTL potential, the worker is in a precarious position, at a height of tens of meters [4], and as a support he is forced to use PTL wires (Fig. 1), which leads to direct contact through the protective suit of various parts of his body with the wires. Here, without taking special measures, almost all the time the worker is on the PTL potential and under load, the distance between his body and the surface of the wires is minimal and is determined only by the thickness of the protective suit (≈ 2 mm). This fact forces during the further analysis to take into account the value of the working flux density of MF, which corresponds to the minimum distance (2 mm) between the worker's body and the PTL wire during exposure for the entire time the worker performs work at the potential.

a *b* *c*

Fig. 1. The typical position of the worker's body when performing work on the PTL potential, where he uses as a support wires under load

The flux density of the MF acting on the worker when performing work at the potential of PTLs and under load was studied by the authors in [16], and their main results are presented in Fig. 2, 3. For example, in Fig. 2, the results of the verified calculation of the maximum value of the flux density of the MF of various PTLs during the performance of works according to the technology adopted by NEC «UkrEnergo» are given. They confirm the need to significantly reduce the iflux density of their MF [16]. Thus, in accordance with the current sanitary standards of Ukraine [33] (item 1 of Table 1), the flux density of the 330 kV PL at the nominal current of its load must be reduced from 11.5 to 7.5 mT when working at a potential of up to 1 hour (Fig. 2). According to the norms of the European Union [12, 32], when working up to 1 hour, a reduction of B_{PD} is required not only for 330 kV PTLs, but also for PTLs 750 kV, N=4. Reduction of flux density of MF for all PTLs is also necessary when t_r is more than two hours.

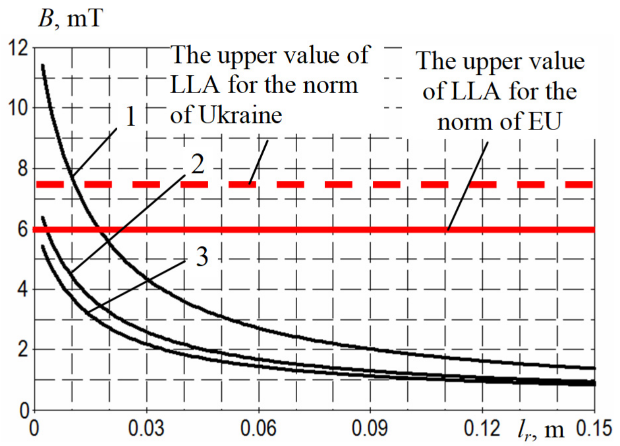

Fig. 2. Dependence of the maximum values of the effective MF flux density of the 330-750 kV PTL in its working zone at the nominal current as a function of the distance l_r from the wire surface to the worker's body (1 – PTL 330, N = 2; 2 – PTL 750, N = 4; 3 – PTL 750, N = 5)

As for the LLA of the MF for the limbs of the worker, which according to Table 1 is 15-18 mT, then there are no special problems with its provision for all PTLs under consideration.

The choice of methods for reducing the flux density of MF when performing work on the potential of PTLs under load. In order to reduce the PTLs' MF when performing work on the potential of PTLs, it is possible to use such well-known methods [38, 39] as shielding and distance protection.

Shielding is widely used when working on the potential PTLs to reduce EF using shielding suits made of electrically conductive material [2-4]. Their use is mandatory. But, as shown in [40-43], such suits do not shield MF of power frequency. This conclusion was also experimentally confirmed by the authors on a laboratory setup (Fig. 4), which consists of an adjustable MF 50 Hz source with flux density of 0-0.6 mT and a magnetometer with a remote sensor fixed in the working area. Measurements of MF flux density were carried out in the absence and presence of a protective suit of the EK-1 shielding kit [4] with material thickness of 2 mm, which covered the sensor. The results of the experiment confirmed the absence of any effect of MF shielding by a protective suit. However, this result was quite expected, since according to [44], only for the implementation of small (1.2-1.5 times) shielding of MF with frequency of 50 Hz, it is necessary to use massive metal conductive (magnetostatic) screens that are at the potential of the wires of PTLs is practically impossible. Therefore, the use of shielding methods to reduce the MF on the potential of the PTL is not considered below.

Distance shielding is widely used to reduce the potential electromagnetic field [10, 45], which decreases with distance from the source. The PTL MF is also potential, which intensively decreases near its wires when moving away from the wire with gradient of about 0.4 mT/mm (Fig. 3).

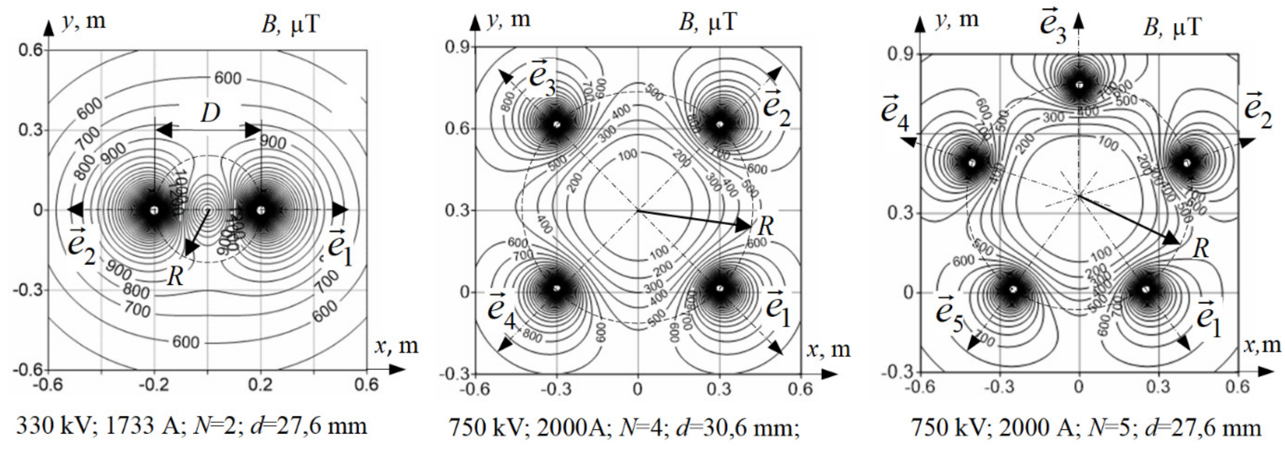

Fig. 3. The nature of the distribution of MF flux density in the working zones of the 330-750 kV PTLs near the split wires of their phases

Fig. 4. Experimental studies of the effect of shielding of MF of powerfrequency with a protective suit of a set of individual shielding EK-1

Therefore, increasing the minimum working distance between the worker's body and the surface of the PTL wires is an effective method of reducing the impact of MF on the worker. In practice, this can be achieved by introducing additional material of the required thickness (2-15 mm) between the wires and the worker's body, which does not deform under the worker's weight. Such a material can be, for example, a special protective suit with increased thickness (10-15 mm), or special capes for PTL wires of the appropriate thickness. For example, with an increase in the working distance from the worker's body to the wires of the 330 kV PTL from 2 mm to 15 mm, and a corresponding increase in l_r, the flux density of MF (Fig. 2) is reduced by almost half – from 11.5 mT to the normative level of 6 mT. Thus, distance protection, based on increasing the working distance to PTL wires, is an effective method of protecting personnel from MF when performing work at potential. But for its practical implementation, it is necessary to introduce new technological operations and special protective means.

The reduction of PTL MF by reducing the operating current I_r of the PTL [16] is called the method of mode load minimization of the PTL. It can be implemented during the repair of PTLs with a corresponding reduction of both the operating current and the flux density of the MF proportional to it. This method is preferable, since its implementation requires only organizational measures agreed with consumers, which provide for planned disconnection of individual consumers during repairs. The effectiveness of using the method of mode load minimization of PTLs to reduce their MF can be expressed through the load factor (k_r) of the PTL, which is defined as the ratio between the operating (I_r) and nominal (I_n) currents of the PTL:

$$k_r = I_r / I_n \,,\ 0 \le k_r \le 1 . \qquad (1)$$

Therefore, the method of mode load minimization of the PTL, which is implemented by reducing the load factor (1) of the PTL for the period of repair, can be recommended as the main method of protecting the working personnel from the PTL MF when performing repair work at their potential. In the event when the use of the main method of protection does not achieve the set goal, together with it, it is recommended to use an additional method of increasing the working distance to the PTL wires based on the use of special protective means – a protective suit with increased thickness of its material (5-15 mm), or protective capes with thickness of 3-13 mm for a guaranteed increase in the distance between the worker's body and the PTL wires.

Definition of conditions for ensuring protection working personnel from PTLs' MF. In order to protect the health of personnel from the effect of MF, it is necessary to guarantee the level of the MF flux density B_R on the body (extremities) of the worker to the limit level of B_{PD}, which is a function of time t_r. Then the conditions of worker's protection can be defined as:

$$B_R(I_r) \le B_{PD}(t_r) \,, \qquad (2)$$

where t_r is working time of the worker at the PTL potential.

As shown by the authors in [16], the maximum iflux density values of MF B_R in the working area of the PTL are concentrated along the axes of symmetry $\vec{e}$ of N suspension of the split wires of its phases (Fig. 3). The MF flux density at the observation point P (Fig. 5) depends on the distance l from the surface of the worker's body (on which the observation point P is located) to the axis of the nearest power line wire, when the x axis coincides with the direction $\vec{e}$.

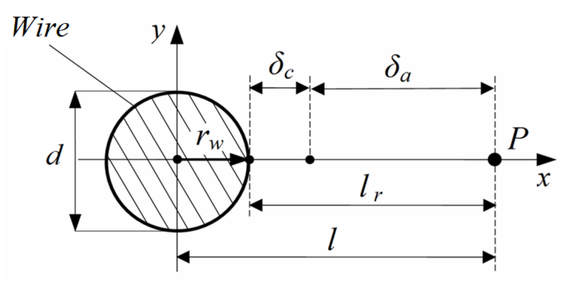

Fig. 5. On the determination of the distance l from the axis of the PTL wire to the observation point P

The MFfluxdensity also depends on such parameters of the transmission line as the number N of split phase wires, their radius r_w, and the distance D between the split phase wires. Here, according to Fig. 5:

$$l = r_w + l_r = r_w + \delta_c + \delta_a \,, \qquad (3)$$

where l_r is the distance from the wire surface to the worker's body; δ_c is the fabric thickness of the standard protective suit of the EK-1 shielding kit (2 mm); δ_a is the thickness of the additional protective layer when using special protective means.

Let us determine the conditions for the implementation of relation (2) when using the method of mode load minimization and the method of increasing the working distance for 3 different types of PTL (Fig. 3), the parameters of which correspond to real (PTL 330 kV, I_n = 1733 A, N = 2, r_w = 14 mm, D = 400 mm; PTL2 750 kV, I_n = 2000 A, N = 4; r_w = 15.4 mm, D = 600 mm; PTL3 750 kV, I_n = 2000 A, N = 5, r_w = 14 mm, D = 500 mm).

To do this, we find the maximum permissible load factors (k_{rD}) of PTLs, which allow limiting the flux density of MF in their working zone to the maximum permissible level of sanitary standards B_{PD}. The value of k_{rD} can be found by using the mathematical model of MF in the working area of the PTL proposed by the authors in [16], taking into account condition (2) and the requirements of sanitary standards from the maximum permissible level of flux density action B_{PD}. As a result, we will get the following calculation ratios that allow us to determine the maximum permissible load factors k_{rD} for different (Fig. 3) PTLs:

$$k_{rD(N=2)} \le \frac{B_{PD}}{I_n}\left[\frac{\mu_0}{2\pi}\frac{(l+R)}{l(l+2R)}\right]^{-1}; \quad (4)$$

$$k_{rD(N=4)} \le \frac{B_{PD}}{I_n}\left(\frac{\mu_0}{2\pi}\left[\frac{(l+R)^3}{(l+R)^4-R^4}\right]\right)^{-1}; \quad (5)$$

$$k_{rD(N=5)} \le \frac{B_{PD}}{I_n}\left[\frac{\mu_0}{10\pi}\left(\frac{1}{l}+\right.\right.$$
$$+\frac{2(l+R-R\cos(2\pi/5))}{(l+R-R\cos(2\pi/5))^2+(R\sin(2\pi/5))^2}+ \quad (6)$$
$$\left.\left.+\frac{2(l+R-R\cos(4\pi/5))}{(l+R-R\cos(4\pi/5))^2+(R\sin(4\pi/5))^2}\right)\right]^{-1};$$

$$R=\frac{D}{2\sin(\pi/N)}. \quad (7)$$

Based on rationships (1) – (7) and item 1 of Table 1, in Fig. 6 graphic dependenceis of k_{rD} for the case are plotted δ_a = 0.

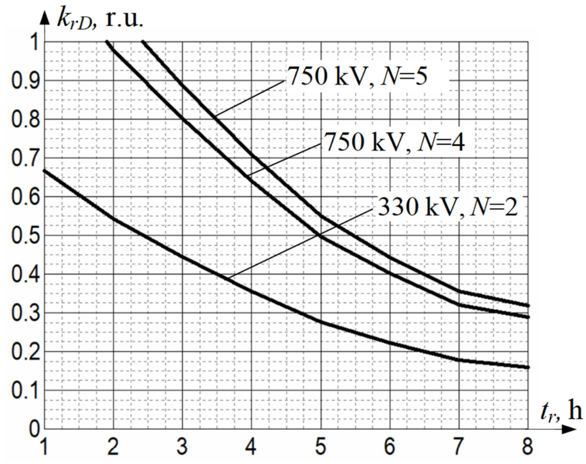

Fig. 6. The maximum allowable load factor k_{rD} of different transmission PTLs at δ_a = 0 depending on the term t_r of works on the potential of PTLs 330-750 kV according to the current standards of Ukraine

From Fig. 6 it follows that the worst situation occurs for the 330 kV PTL. Its maximum permissible load factor k_{rD} already at t_r = 1 h should be less than 0.67, at t_r = 4 h – 0.36, and at t_r = 8 h – 0.16. But the practical achievement of low load factors (k_r < 0.5) can be problematic, and especially, with a large amount of repair work on PTLs, the execution of which requires a significant amount of time.

For 750 kV PTLs with a large number of split wires (N = 4; 5) and at t_r = 1 h, k_{rD} of the PTL (Fig. 6) is close to 1, at t_r = 4 h – 0.65-0.7, and at 8 hours – about 0.29-0.32. For these PTLs, the use of the mode load minimization method may be sufficient when $k_{rD} \ge 0.5$ and t_r < 5 hours.

The joint use of the mode load minimization method and the method of increasing the working distance may be appropriate for 330 kV PTLs with t_r > 1 h, and is illustrated by the curves in Fig. 7, constructed in accordance with relationships (1)-(7) and item 1 of Table 1.

Thus, when an additional distance δ_a = 5 mm is introduced, the coefficient k_{rD} for this PTL can be increased in the entire range of t_r by up to 30%, at δ_a = 10 mm – up to 60%, and at δ_a = 15 mm – almost twice. This confirms the high efficiency of the method of increasing the working distance. The joint use of the proposed methods may also be appropriate in case of high labor intensity of works on the PTL potential, or in the case of the impossibility of significantly reducing the coefficient k_{rD} by the mode load minimization method.

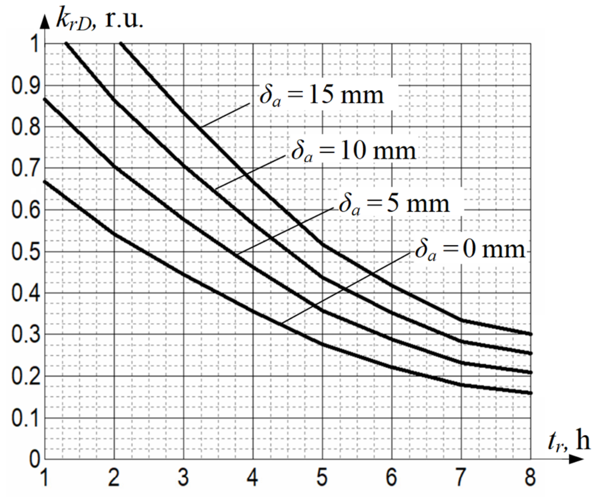

Fig. 7. The maximum allowable load factor k_{rD} of the 330 kV PTL (N = 2) in case of introducing an additional working distances δ_a according to current standards of Ukraine

The set of methods proposed above for reducing the MF acting on the worker, and the developed methodology for calculating the maximum allowable load factor k_{rD} of the PTLs, as well as the fulfillment of the formulated condition (2), constitutes the methodology for protecting workers from the magnetic field of the PTLs.

Now let's evaluate the effectiveness of using the considered methodology of worker's protection to reduce the flux of the PTL MF to the stricter Standards of the

European Union [12]. But in [12] normalization of only the upper (6 mT) and lower (1 mT) LLA of the MF flux density is provided, and there is no normalization for different working hours of employees (between 1 and 8 hours), as it is done in [33, 34]. In order to perform the specified assessment, we will supplement the standard [12] with the values of the LLA of the MF flux density as a function of the staff's working time t_r according to the methodology of the National Academy of Medical Sciences of Ukraine used in [33, 34].

Thus, as follows from the analysis of the current regulations in Ukraine [33, 34] developed by the Institutes of the National Academy of Medical Sciences of Ukraine, the dependence $B_{PD} = f(t_r)$ on them is expressed by an exponential function:

$$B_{PD} = be^{-at_r}, \quad (8)$$

which, according to the data of item 1 of Table 1, presented in the form of curve 1 in Fg. 8.

Let's use (8) to determine the possible dependence $B_{PD} = f(t_r)$ for the implementation of European Union Standards. Such a dependence at a = 0.2560, b = 7.7503 is presented in the form of curve 2 in Fig. 8, and the B_{PD} values calculated on its basis, marked with asterisks, are summarized in item 2 of Table 1. It is obvious that when implementing European Union Standards [12, 33] in Ukraine, the dependence $B_{PD} = f(t_r)$ needs clarification based on the latest research of the National Academy of Medical Sciences of Ukraine.

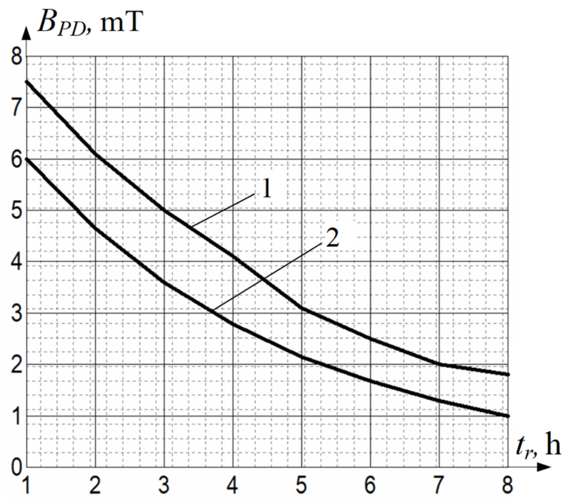

Fig. 8. Dependence of the limit level of MF flux density B_{PD} for the body of the worker on time t_r in accordance with current 1 [33] and promising 2 [12, 32] sanitary standards

Built in accordance with the data of item 2 of Table 1 dependencies $k_{rD} = f(t_r)$ at δ_a = 0 for European Union standards are presented in Fig. 9. Their analysis shows that for the worst case (330 kV PTL), already at t_r = 1 h, the coefficient k_{rD} of the PTL should be no more than 0.53, at t_r = 4 h – 0.25, and at t_r = 8 h – 0.09. Therefore, the implementation of European Union Standards (item 2 of Table 1) without using additional methods of increasing the working distance can be problematic.

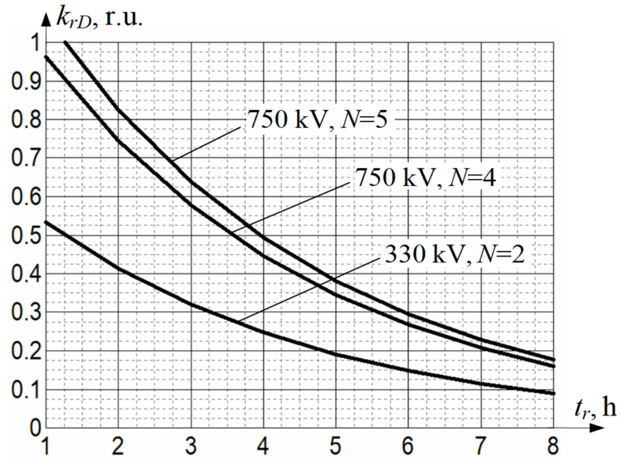

Fig. 9. The maximum allowable load factor k_{rD} according to prospective Standards of the European Union (item 2 of Table 1) of various PTLs depending on the term of performance t_r of works on the potential of 330-750 kV PTLs at δ_a = 0

The results of ensuring the standards of the European Union [12, 32] when using an additional distance protection method are presented in Fig. 10.

Here, the maximum allowable load coefficients k_{rD} are determined in accordance with (1)-)8) and item 2 of Table 1 at δ_a from 0 to 15 mm. Their analysis shows that for the worst case (330 kV PTL) it is possible to reach the regulatory value of B_{PD} already at k_{rD} = 0.5 for t_r < 4 h, and δ_a = 15 mm. The obtained results confirm the possibility of compliance with the European Union norms (item 2 of Table 1) when using the developed methods of protecting workers from the PYLs MF.

Presented in Fig. 6, 7, 9, 10 graphical dependencies allow to quickly, in working conditions, implement the developed methodology of protection of workers from MF of 330-750 kV PTLs with the implementation of both the current sanitary standards of Ukraine and the Directives of the European Union.

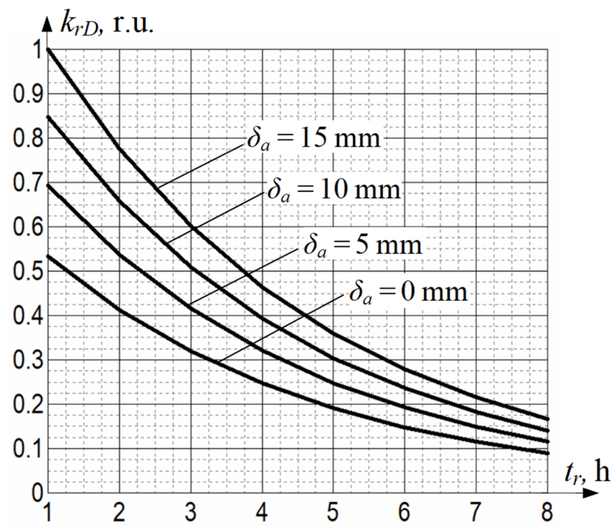

Fig. 10. The maximum permissible load factor k_{rD} according to the perspective Standards of the European Union (item 2 of Table 1) for 330 kV PTLs, depending on the term of completion of works t_r on the potential in case of introducing an additional working distance δ_a

Conclusions.

1. It is shown that practically during the entire time the worker is working on the potential of the wires of the power transmission lines using the technology of NEC «UkrEnergo», a minimum distance (≈ 2 mm) is maintained between the worker's body and the surface of the wires, which is determined by the thickness of the EK-1 protective suit. This circumstance should be taken into account when determining the flux density of the magnetic field acting on the worker during work on the potential of power transmission lines.

2. The methods of reducing the magnetic field in the working area of power transmission lines are proposed, such as the method of mode minimization of its load factor for the duration of the repair, and the method of increasing the working distance by introducing additional material of certain thickness (2-15 mm) between the wires and the worker's body, the use of which allows to reduce the flux density of the magnetic field when performing work on the potential of power transmission lines to a safe level.

3. A methodology for calculating the maximum permissible load factor of power transmission lines 330-750 kV has been developed, the use of which allows limiting the flux density of the magnetic field in their working zones to the maximum permissible level of sanitary standards for a given period of work on the potential and a given thickness of the additional protective layer between the wires and the worker's body.

4. Methodological principles for the protection of workers from the magnetic field during repair work without removing the voltage under load on 330-750 kV power transmission lines have been created, based on the combined use of the developed method of mode minimization of the load factor and the method of increasing the working distance, and a method has been developed of calculating the maximum allowable of the load factor under the condition of limiting the level of the magnetic field to the normative one. Their implementation makes it possible to reduce the flux density of the magnetic field in the working area of power transmission lines to the maximum permissible value in accordance with both current and future sanitary standards.

5. The obtained results can form a scientific basis for the development of normative documents of the Ministry of Energy, which regulate the rules of safe work of personnel in the magnetic field during repair work on 330-750 kV power transmission lines without voltage removal and under load.

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

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