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# Technology of personnel protection from the electromagnetic field in electrical installations of ultrahigh voltage classes

***Abstract**. The risk formation mechanisms of occupationally determined diseases of personnel from the action of electromagnetic field of industrial frequency in electrical installations of ultrahigh voltage classes (UHVC) for its estimation are investigated. The main possible causes of electric injury and occupationally determined diseases during repair work on the hot air lines of UHVC are considered. The model of "fault tree" in the case of the protective clothing destruction in the course of work is proposed. The substantiation of the maximum permissible parameters of electrical safety is given, taking into account the value of the maximum permissible electric energy. A system of continuous monitoring of the permissible energy levels absorbed by the body of personnel and signaling in case of exceeding the permissible level is proposed.*

***Streszczenie.** Badane są mechanizmy powstawania ryzyka chorób zawodowych personelu na skutek działania pola elektromagnetycznego o częstotliwości przemysłowej w instalacjach elektrycznych o klasach ultra-wysokiego napięcia (UHVC) w celu jego oszacowania. Uwzględniono główne możliwe przyczyny urazów elektrycznych i chorób zawodowych podczas prac remontowych na działających liniach napowietrznych UHVC. Zaproponowano model "drzewa urazowego" w przypadku zniszczenia odzieży ochronnej w trakcie prac. Podane jest uzasadnienie maksymalnych dopuszczalnych parametrów bezpieczeństwa elektrycznego, uwzględniające wartość maksymalnej dopuszczalnej energii elektrycznej. Proponuje się system ciągłego monitorowania dopuszczalnych poziomów energii pobieranej przez personel i sygnalizacji przekroczenia dopuszczalnego poziomu. (**Technologia ochrony personelu przed polem elektromagnetycznym w instalacjach elektrycznych ultra-wysokiego napięcia**).*

**Keywords:** *electrical safety, electromagnetic field, ultrahigh voltages, risk, disease, electrical energy.*
**Słowa kluczowe:** bezpieczeństwo elektryczne, pole elektromagnetyczne, ultra-wysokie napięcia, ryzyko, choroba, energia elektryczna.

## Problem statement

Industrial ultrahigh voltages (UHVC) 330, 500, 750 kV electrical installations of industrial frequency are the main components of the unified power grid of Ukraine. They provide optimal load of power plants, reducing energy consumption compared to low and high voltage networks. However, UHVC electrical installations have created a number of additional problems, among which the most important is the electrical safety control during their maintenance and repair [1]. UHVC electrical installations are one of the main sources of industrial frequency electromagnetic field (IFEF), which has a harmful effect on the health of personnel. In case of exceeding the levels of IFEF, changes in the functional state of the nervous, endocrine, immune and cardiovascular systems of the human organism are possible [2, 3] and, as a consequence, the risk of occupational diseases for personnel who perform long-term work in UHVC electrical installations.

Risk assessment is envisaged by the European Union Core Directive 89/391/EEC and its subordinate directives on safety at work (89/654/EEC, 89/655/EEC, 90/269/EEC, etc.). The above substantiates the relevance of the scientific problem, which is to improve the technology of personnel protection from the action of an electromagnetic field of industrial frequency in the UHVC electrical installations to achieve the required level of electrical safety [4, 5].

The purpose of the article is to increase the electrical safety of personnel from the action of an industrial frequency electromagnetic field in ultrahigh voltage electrical installations by substantiating the causes and nature of the electromagnetic field effect and the permissible energy level absorbed by the body of the personnel for the proposed technology for performing live work.

## Analysis of recent research and publications

An analysis of research and publications has shown that the requirement of absolute safety in UHVC electrical installations seems unattainable. Despite the significant contribution of Alexandrov G.N., Dolin P.A., Dovbysh V.N., Kumamoto H., Kulmatytsky O.I., Marshall V, Malinovsky A.A., Morozov Y.A., Tikhodeev M.M., Silvester P., Chari M. [1, 2, 3] and other authors in the development of the theory of electrical safety and risk of injuries, theoretical aspects of the assessment of the risk of electro-traumatism and occupationally determined diseases of personnel interacting with UHVC electrical installations, to develop a complex of electrical safety measures, aimed at minimizing it are not studied properly [4, 5, 6]. The analysis of the published works has shown that today there is no theoretical basis for the construction of an electrical safety system aimed at minimizing the risk of electro-traumatism in UHVC electrical installations [7, 8]. Known methods of estimating the level of electrical safety are based on a comparison of the measured calculated values of the electromagnetic field, touch voltage, the current passing through the human body, and their time of their action with the normalized parameters or statistics of electrical injury methods of analysis without taking into account the probabilistic nature of electrical injury and occupationally determined diseases of the personnel from the action of electricity [7].

## Basic research

In order to identify the risks of electro-traumatism in UHVC electrical installations based on the proposed classification of known approaches and methods for assessing and analyzing the risk of electro-traumatism, cited in [7, 9], the authors developed a model of an "event tree" for the development of electro-trauma in "human – UHVC electrical installation – environment" system, which is presented in Fig. 1.

This figure shows the possible causes of electrical injury and occupationally determined diseases when performing repair work in hot air lines of the UHVC. The main event (E) for this model is assumed to be the result of the simultaneous imposition of three prerequisites: person’s staying in the coverage of electric energy (H), real dangerous and harmful values of industrial frequency alternating current in the area of the technological work of the UHVC electrical installations (W), and failure of protective equipment (P).

Therefore, the main starting conditions for electrical injury and occupationally determined diseases in the maintenance and repair of UHVC electrical installations are: personnel staying in the coverage of electric power; the real existence of dangerous values of electricity; lack or ineffectiveness of protective equipment and erroneous and unauthorized actions of personnel in this situation.

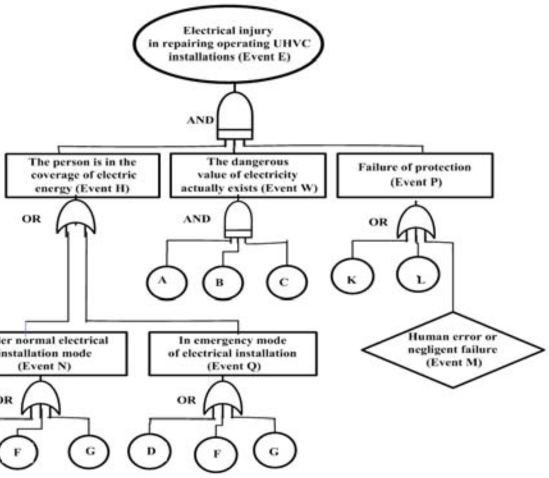


Fig. 1 – Model of the "event tree" of electrical trauma development during hot work in UHVC electrical installations.

Therefore, the main starting conditions for electrical injury and occupationally determined diseases in the maintenance and repair of UHVC electrical installations are: personnel staying in the coverage of electric power; the real existence of dangerous values of electricity; lack or ineffectiveness of protective equipment and erroneous and unauthorized actions of personnel in this situation.

The analysis of these transitions revealed inaccuracies of the permissible limits of hygienic classes according to the hygienic classification of the stress of IFEF and enabled the authors to propose new maximum permissible limits of the action of electricity on personnel for the further development of the matrix method of "danger probability – losses" assessment of electro-traumatism risk in UHVC electrical installations [10,13,17].

The analysis of the conditions of the electromagnetic field protection system for works on the potential of the UHVC airline wires according to the “failure tree” model (Fig. 2) made it possible to substantiate the feasibility of using continuous control of the protective properties of the shielding protective clothing during the work on the hot parts of the UHVC electrical installations.

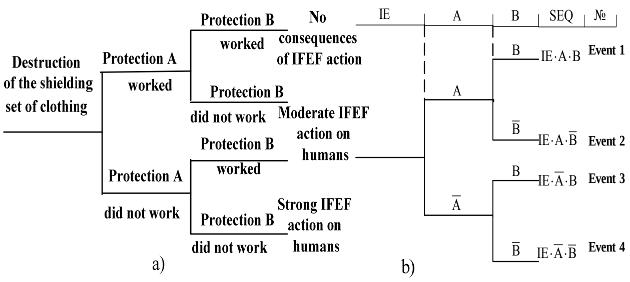


Fig. 2 – "Failure tree" model for the case of shielding clothing damage when working on UHVC airline wires (a) and a formal representation of the "failure tree" for the specified case (b)

In the "failure tree" model presented in Fig. 3 additional conditions are as follows: there are two degrees of protection: A – continuous control of the screening properties of the shielding clothing and alarm in case of exceeding the norm by [10, 11, 12] and B – additional screening of the worker using an electrician chair that is provided by the procedure in accordance with [7]. As it can be seen from the "failure tree" model, for the case of the destruction of the shielding clothing when working on hot UHVC airline wires (Fig. 2) when using technologies without an electrician chair, a strong effect of IFEF on personnel is possible [14,15,16,17].

**Methodological indicators of the maximum permissible parameters of electrical safety taking into account the value of electricity alarm levels.**

On the basis of the combined approach, taking into account the real parameters of the person, the contact voltage and currents passing through the body of the worker, operating sanitary and hygienic norms, by combining the numerical method of estimating the allowable level of electrical power and the time of stay of the worker under the influence of IFEF the mathematical model of determination of the value of the allowable electric energy for the body of an average worker was obtained, which made it possible to substantiate the quantitative value of the maximum allowable value of the electric energy absorbed by the worker 's body, in interaction with UHVC electrical installations. The maximum permissible energy for the body of the worker in this case, according to the example of calculation, is 0.36 J.

For the model variant of the allowable time of human stay under the influence of an electric field of industrial frequency, the value of the allowable energy $W_{h.dop.}$ in W/h absorbed by the human body is obtained from the expression:

(1) $$W_{h.dop.} = P_{h.dop.} \cdot t_{dop.}$$

where $P_{h.dop.}$ is the permissible value of the power of electromagnetic energy absorbed by the human body, W; $t_{dop.}$ is the permissible time of stay of the person in the electric field at the appropriate level of power absorbed by the body of the person, h.

The value of the industrial frequency power in watts absorbed by the human body is obtained from the known expression (2):

(2) $$P_{h.dop.} = \frac{2 \cdot \pi \cdot a \cdot b^2 \cdot \rho_h \cdot \omega^2 \cdot \varepsilon_0^2 \cdot E^2}{3N_a^2},$$

where *a, b* – the semi axes of the elongated half-ellipsoid rotation corresponding to the size of the human body;
$E$ – electric field strength, V / m;
$\rho_h$ – specific resistance of the human body, Ω;
$\omega$ – angular frequency, s$^{-1}$; $\varepsilon_0$ = 8,85·10$^{-12}$ – dielectric constant, F/m; $N_a = \frac{b^2}{a^2}[(\ln\frac{2a}{b}) - 1]$ – the depolarization factor of an ellipsoid rotation along the semi axes of rotation a, which is equivalent to the volume of a human body, provided that *a/b* >10.

The numerical value for $W_{h.dop.}$ is determined by the condition that for the body of the average person weighing 71,9 kg and average height *a* = 1,7 m, *b* = 0,14 m, the resistivity is estimated by the value $\rho_h = 150 \div 200$ Oh·m and for the electric field strength $E = 5 \cdot 10^3$ V/m strength the permissible time of a person's stay in the electric field is 8 hours. Under this condition, substituting expression (2) in (1), the numerical value for $W_{h.dop.}$ in joules is obtained:

(3) $W_{h.dop.} = 1{,}223 \cdot 10^{-5} \cdot 8 \cdot 3600 = 0{,}36.$

Field energy is dissipated in body weight. The expression (2) is obtained for the permissible energy absorbed by the body of the human being in the IFEF of the mass, 71.9 kg. Under real conditions, the mass of a particular person differs from the average, so a correction factor k which is defined as the allowable energy, which is defined as $k = m_h / 71.9$ where $m_h$ is the mass of the real person who is in the IFEF, and

(4) $W_{h.dop.} = 0{,}36\text{kJ}$

Assuming that a person's body volume, its specific resistance, and angular frequency do not change over time, then expression (2) is

(5) $P_{h.dop.} = n \times E^2, \text{W}$

where

(6) $$n = \frac{2 \cdot \pi \cdot a \cdot b^2 \cdot \rho_h \cdot \omega^2 \cdot \varepsilon_0^2}{3N_a^2}, \ \text{m}^2/\Omega$$

Substituting expression (3) and (4) in (1), we obtain an expression for the allowed time of a person in the IFEF (in hours) from the electric field intensity for the range from 5 kV / m to 20 kV/m:

(7) $$t_{dop.} = \frac{0{,}36 \cdot k}{3600 \cdot n \cdot E^2}.$$

Substituting (5) into (6), we obtain a simplified expression for the permissible time (in hours) of a person's stay in the IFEF from the electric field strength for the range from 5 kV/m to 20 kV / m:

(8) $$t_{dop.} = \frac{200 \cdot k}{E^2},$$

where E is the electric field strength, kV/m.

The obtained expression (7) made it possible to construct a dependence between the maximum allowed time and the electric field intensity, taking into account the set value of the maximum allowable energy (Fig. 4), which is the basis of the proposed method for determining the allowed time of personnel stay in the electric field of the UHVC electrical installations.

In Fig. 3 shows the dependences of the allowable residence time in the IFEF on the field strength for State Standard (GOST) 12.1.002-75 – curve 1, State Standard (GOST) 12.1.002-84 and State sanitary rules and regulations (DSanPin) 3.3.6.096-2002 – curve 2 and the proposed dependence – curve 3.

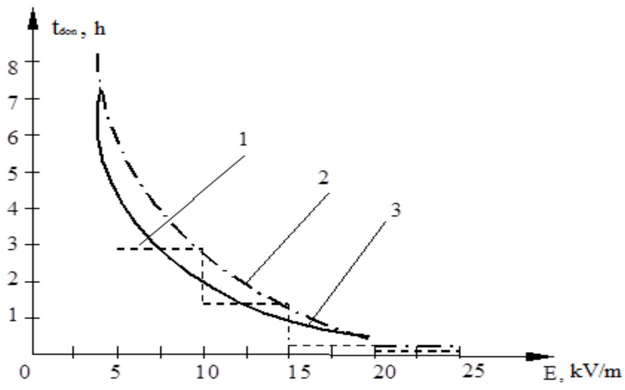

Fig. 3 – Graphs of dependences of the allowable time of stay in an electric field on the intensity of IFEF

From the above dependencies (Fig. 4) we can conclude that the observance of the requirements for the allowable time of stay of a person under the influence of an electric field of industrial frequency in the range from 10 to 15 kV/m reduces the risk of occupational disease for electrotechnical staff within the range of the electric field of UHVC electrical installations, in contrast to the applicable standards currently used in Ukraine.

For quantitative risk validation of occupationally determined diseases of the personnel, a comparative values characteristic of the allowed time of stay of the person in IFEF, the power and energy of the electric field absorbed by the human body, for different values E (parameters of the human body: mass 71.9 kg, a = 1.7 m, b = 0,14 m, $\rho_h$ 200 Ω·m) = 200 Ω m) according to State Standard GOST 12.1.02-84 [8] and State sanitary rules and regulations (DSanPin) 3.3.6.096-2002 [9] and those proposed in Table. 1.

Comparative analysis of maximum permissible values according to table 1 has shown the advantage of the proposed method for determining the allowed time of stay of the worker in the electric field, taking into account the action of electric energy. A worker staying within the coverage of IFEF from 10 kV/m to 15 kV/m, at the value of the allowed time determined for [8] and [9], the worker absorbs electricity approximately one and a Table 1 – Comparative analysis of maximum permissible values of the worker's stay in IFEF, power and energy of the electric field in accordance with State Standard GOST 12.1.002-84 and State sanitary rules and regulations (DSanPin) 3.3.6.096-2002 and those suggested half times the maximum permissible value, than for the range from 5 kV/m to 10 kV/m, which, accordingly, increases the risk of occupationally determined disease from the action of IFEF.

Table 1. Maximum permissible values of the worker's stay in IFEF, power and energy of the electric field

| $E$, kW/m | State Standard GOST 12.1.002-84 and State sanitary rules and regulations (DSanPin) 3.3.6.096-2002 | | | suggested | | |
|---|---|---|---|---|---|---|
| | $P_{h.dop.}$, μW | $t_{dop.}$, h | $W_{h.dop.}$, J | $P_{h.dop.}$, μW | $t_{dop.}$, h | $W_{h.dop.}$, J |
| 5 | 12 | 8 | 0,36 | 12 | 8 | 0,36 |
| 10 | 50 | 3 | 0,53 | 50 | 2 | 0,36 |
| 15 | 110 | 1,3 | 0,49 | 110 | 0,9 | 0,36 |
| 20 | 200 | 0,5 | 0,36 | 200 | 0,5 | 0,36 |

**Conclusions.**

Existing electrical safety technologies in high-voltage electrical installations do not provide the necessary level of safety against the action of electrical energy. electrical injury of the human body while performing work in electrical installations occurs due to the amount of certain events, which include: human error, failure of electrical equipment, adverse external action, the appearance of a dangerous factor (electrical energy) in an unexpected place and at the wrong time; the absence or malfunction of the protective equipment provided for in these cases and the inaccurate actions of the worker in such a situation; spreading and influence of dangerous factors on the worker.

The proposed concept of increasing the level of electrical safety, based on the models of "event tree" and "failure tree", provides not only protection of the worker's life, but also protection from occupationally determined disease during the work in the UHVC electrical installations, due to the continuous control of electrical energy absorbed by the body of the personnel.

Obtained models of raising the level of electrical safety system for personnel interacting with UHVC electrical installations have made it possible to get previously unknown patterns in the process of causing electrical injury in the UHVC electrical installations.

For the first time, the dependences between the allowable time and the electric field strength of the IF, the allowable touch voltage, the maximum allowable current of the industrial frequency and its time are obtained, taking into account the set value of the maximum allowable energy of 0.36 J, which is absorbed by the body of the worker, which in turn made it possible to numerically substantiate the maximum permissible parameters of electrical safety, and to technically improve the system of personnel protection working directly or near the conductive parts of electrical installations of UHVC and to evaluate by quantitative and qualitative indicators the risk of electrical injury and to transform the estimates obtained into valid and targeted preventive measures for electrical safety.

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