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Evaluation of the risk of occupation a diseases caused by electromagnetic field generated by extra-high voltage electric installations

***Abstract**. Researched were the regularities in formation of the risk of occupational disease in staff caused by industrial-frequency electromagnetic field in extra-high voltage electric installations for further evaluation. Considered were the main conditions of electrical safety systems (optimum, permissible, harmful, dangerous) and possible transitions between them depending on the magnitude of the electric power, absorbed by employee's body. Proposed are new levels of working conditions associated with electric power effect under proposed techniques. Set forth are the results of evaluation of occupational disease risk using probit-function and the recommendations regarding the arrangements aimed at reduction thereof.*

***Streszczenie.** W pracy badano regularność w występowaniu ryzyka choroby zawodowej pracowników, spowodowane przez pole elektromagnetyczne, o częstotliwości przemysłowej w wysokonapięciowych instalacjach elektrycznych. Rozpatrywane były główne warunki bezpieczeństwa instalacji elektrycznych (optymalne, dopuszczalne, szkodliwe, niebezpieczne) oraz możliwe przejścia między nimi, w zależności od wielkości energii elektrycznej, pochłanianej przez ciało pracownika. Zaproponowano nowe poziomy warunków pracy, związane z oddziaływaniem mocy elektrycznej, związanych z proponowanymi technikami. W pracy podano wyniki oceny wystąpienia ryzyka choroby zawodowej z wykorzystaniem modelu probit oraz zalecenia, dotyczące ustaleń mających na celu ich zmniejszenie. (**Ocena ryzyka wystąpienia chorób zawodowych wywołanych przez pola elektromagnetyczne generowane przez instalacje elektryczne najwyższego napięcia**).*

Keywords: electromagnetic field, risk, disease, electric installation, electric power.
Słowa kluczowe: pole elektromagnetyczne, ryzyko, choroby, instalacja elektryczna, energia elektryczna.

Introduction

The Extra-high voltage (EHV) electric installations of industrial frequency 330, 500, 750 kV represent one of the main components of Ukraine's integrated power system, they ensure optimum load of power stations and reduction of power consumption as compared to lower-voltage grids.

At the same time, EHV electric installations represent one of major sources of industrial-frequency electromagnetic field (IF EF), which affects the health of staff members. The issue of determination of electromagnetic environment generated by industrial frequency overhead EHV lines is considered in research papers by P.O. Dolin, G.N. Aleksandrov, M.M. Tihodeev, Yu.O. Morozov, V.N. Dovbush, V.M. Kutin, P. Silvester, M. Chari [1-5] and other authors.

In case of excess IF EF levels as compared to permissible ones, possible are changes in functional condition of human body's nervous, endocrine, immune and cardiovascular systems [6-8] and as a result, the risk of occurrence of occupational diseases in staff members, who work at EHV electric installations or prolonged periods of time.

Risk evaluation is provided for by main European Union Directive 89/391/EEU and special directives relating to workplace safety (89/654/EEU, 89/655/EEU, 90/269/EEU and others) subordinated to it.

Ukraine's applicable standards [9-10] that guarantee occupational safety in IF EF conditions do not take into account the probabilistic cause-and-effect nature of electric injuries, particular staff member's parameters and the interrelation with the amount of energy absorbed by his or her body. The foregoing substantiates the relevance of developing the techniques for evaluating the risk of occupational diseases in staff caused by EHV electric power installations.

Research objective. Based on the applicable hygienic classification of working conditions, and using the systemic and risk-oriented approaches to develop and improve the techniques for evaluating the risk of occupational diseases in staff caused by electric power effects, as well as the arrangements aimed at minimization thereof.

Model for research of electrical safety systems conditions caused by effects of industrial-frequency electromagnetic field

In order to evaluate the risk of electric injury frequency, selected was the cause-and-effect model of electric injury frequency in the following form: human error, electric equipment failure and adverse external action; occurrence of dangerous factor (electric power or parameters characterizing the same) in an unexpected place and ill-timed; absence or malfunction of the protection means envisaged for such cases and employee's inaccurate actions in such a situation; dangerous factors' expansion and effect on the employee.

When determining the criticality of IF EF effect consequences on the staff engaged in process works at EHV electric installations, it is proposed to use the hygienic classification of work as regards indicators of harm and danger of production environment factors and intensity of working process, which is effective in Ukraine as of today and approved by the Decree of the Ministry of Health of Ukraine dated April 08, 2014 under No. 248 [9]. Pursuant to [9], working conditions are divided into 4 classes:

- class one (optimum working conditions) – the conditions, under which not only workers' health is preserved, but also the background is formed for maintenance of high-level working ability;
- class two (permissible working conditions) – characterized by such levels of production environment and working process factors that do not exceed the established hygienic standards, while possible changes in body's functional condition are renewed in the time of scheduled rest or prior to beginning of the next shift without producing any adverse effect on workers and on their offsprings in the nearest and long-term periods;
- class three (harmful working conditions) – characterized by such levels of harmful production factors, which exceed hygienic standards, capable of producing adverse effect on

workers and/or on their offsprings. According to the level of violation of hygienic standards and possible changes in workers' bodies, they are divided into 4 degrees: degree 1 (3.1), degree 2 (3.2), degree 3 (3.3), degree 4 (3.4);

- class four (dangerous working conditions) – characterized by such levels of harmful production environment factors and working process, the effects of which during a working shift (or any part of shift) create danger to life, a high risk of occurrence of severe and acute forms of occupational injuries.

Working conditions of one or another harm and danger class under the influence of industrial frequency electric field are classified pursuant to [11] (see table 1), the values of maximum permissible levels (MPL) of which are selected pursuant to SSN 3.3.6.096-2002.

Table 1. Class of working conditions affected by electromagnetic radiation (exceeding MPL, one times) for [11] and which are offered

Productions effects factor	Class of working conditions for [2]					
	Acceptable 2	Harmful 3				Dangerous (extreme) 4
		1 degree 3.1	2 degree 3.2	3 degree 3.3	4 degree 3.4	
IF electric fields (50 Hz)	$\leq$ MPL (for the entire working day)	≤ 3	≤ 5	≤ 10	> 10	> 40

According to the results of theoretical and experimental investigations of electromagnetic field in 330-750 kV electric installations it was found that evaluation of electrical safety of staff's staying under electromagnetic field of EHV electrical installations of IF EF voltage, as per the applicable norms, results in a multiple-valued determination of protection means (screens etc.) not only under inhomogeneous fields, which is typical for EHV switching devices, when operating at cable potential and nearby earthed structures, but even under the fields close to homogeneous. Besides, weather conditions, land topography and staff themselves, who are affected by IF EF, do strongly distort the external electromagnetic field. Research results prove that the requirement to ensure absolute safety in EHV electric installations is unreal to observe. Staff activity at EHV electric installations is associated with a certain initial risk of electric injury and occupational disease. Therefore, according to the strategy of electrical safety at EHV electric installations, it is advisable to accept the method of electric injury risk minimization, pursuant to which "Any risk should be minimized insomuch as this is reasonably practicable".

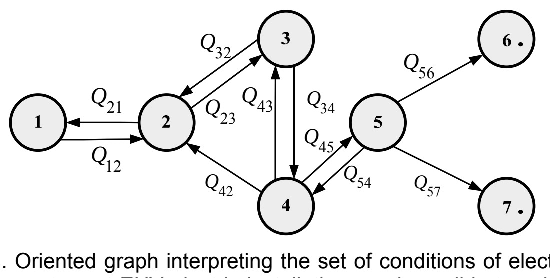

Fig.1. Oriented graph interpreting the set of conditions of electrical safety system at EHV electric installations and possible transitions between them

When modeling the conditions of occurrence of staff occupational diseases caused by industrial frequency electric field using the graphical method of oriented graphs, developed was the oriented graph of electrical safety system conditions during process works at EHV electric installations, which is shown in the figure 1 below. This enabled us to analyze electrical safety conditions for "employee–electric installation–environment" system and possible transitions between them with an allowance for the cause-and-effect pattern selected.

According to the figure, the process of occupational disease in the course of process works at EHV electric installations characterizes seven conditions of electrical safety system, of which the first five ones (optimum, permissible, harmful of 3.1 degree, harmful of 3.2 degree and harmful of 3.3 degree) are somewhat transitional, with the last two ones (critical and fatal) – absorptive.

The analysis of conditions of electrical safety system using the oriented graph proved that determination of risk associated with working conditions at IF EF to staff under hygienic norms [11] at EHV electric installations is actually impossible under the following circumstances:

– explanations regarding the allocation of working conditions to one or another harm class under Table 1 do not produce any unambiguous concept. Thus, harm degree classes 3.1, 3.2, 3.3 are provided with mathematical sign $\leq$ which does not determine any particular boundaries for exceeding the upper permissible levels (MPL) of IF EF. For instance, it would be mathematically correct to refer twofold excess of MPL at IF EF to harm degrees 3.1, 3.2 and 3.3. As for the mathematical expression > 10, harm degrees of class 3.4 working conditions, the boundaries of exceeding the 10 number should also be indicated, since the numerical value of MPL excess (over forty) is specified for dangerous working conditions,
– hygienic classification [11] does not take into account the probability of severe consequences for staff health in case of MPL excess during the process works at operating EHV electric installations,
– hygienic classification [11] does not provide any explanations on determination of quantitative components of evaluating the group risk and on adjustment thereof for each particular person's parameters (weight, height, age, health status and others) aimed at determination of individual risk of electric injury frequency.

Ukraine's applicable DSanPiN 3.3.6.096-2002 and GOST 12.1.002-84 standards that guarantee people's occupational safety under industrial frequency electrical fields do not take into account the interrelation with the amount of energy absorbed by employees' bodies.

In this connection, it is proposed to determine the severity of consequences of working under industrial-frequency electromagnetic field, in terms of working conditions, depending on the value of excess of maximum permissible level of electric power (times) absorbed by the bode of an employee staying under IF EF.

Methodological indicators of risk of occupational disease caused by industrial-frequency electromagnetic field in terms of working condition

Since, in terms of safety, experimental data of electric power values dangerous for human body are restricted, and in view of the fact that one and the same value of dangerous factor (amount of power absorbed) may generally cause consequences of various severity in different people (i.e. the effect of injury is of a probabilistic nature), it is proposed in these conditions of insufficient statistical data for determination of characteristics of probability of electric power effect of humans, to use the well-known method of probit-function, the idea of which belongs to an American entomologist Ch. Bliss [12]. The method of "probit-analysis" has been developed and now being used in biology, toxicology, pharmacology, environmental science and other research areas.

It is known that probit-function is a mathematical dependence that connects the specificities of threatened adverse effect on a certain object and the amount of possible harm. Practically, in majority of cases of safety hazards, the probit-function expression is used that has the following form [13]:

(1) $$Pr = a + b \cdot lnD,$$

where *a*, *b* are the ratios characterizing the degree of protection object's exposure to particular hazard, *D* is the "adverse effect evaluation".

In the event of an electrical injury, pursuant to [14], the value of complex criterion of electric shock hazard is assumed as *D* parameter showing by how many times the electric power $W_{h.}$ that is absorbed by human body exceeds the permissible value of $W_{h.don}$ (*D* value should be no lower than 0.1), that is:

(2) $$D = W_{h.} \big/ W_{h.don.}.$$

The expression used to reflect the risk of electric injury, as determined using the probit-function method, pursuant to [12], looks as follows:

(3) $$R = 2,5 + 0,7 \cdot ln(W_{h.} \big/ W_{h.\ don.}).$$

The permissible time of a human exposed to electrical field of industrial frequency, the values of industrial energy $W_{h.don}$ expressed by *W*·hour absorbed by a human body were obtained from the expression:

(4) $$W_{h.don.} = P_{h.don.} \cdot t_{h.don.}$$

where $P_{h.don}$ is the permissible value of electromagnetic energy power, which is absorbed by a human body, W; t_{don} is the permissible time of human exposure to the electic field of respective power levels, which is absorbed by a human body, hours.

The W-values of power of industrial frequency, which is absorbed by a human body were obtained, according to [13], from the known expression:

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

where a, b are the semi-axes of the oblong semi-ellipsoid of rotation, which correspinds to the human body size; *E* is the electric field voltage, V/m; ρ_h is the specific human body resistance, Ohm·m; ω is angular frequency, s^{-1}; $\varepsilon_0 = 8.85 \cdot 10^{-12}$ is the dielectric constant, F/m; $N_a = \frac{b^2}{a^2}\left(\ln\frac{2a}{b} - 1\right)$ is the depolarization factorof the ellipsoid of rotation along the rotation semi-axis *a*, which is equivalent to the human body volume, provided that $\frac{a}{b} \geq 10$.

The numerical value for $W_{h.don}$ was determined under the stipulation that for the body of an average human with the 71.9 kg body weight and $a = 1.7\ m$ average height, $b = 0.4\ m$, the specific resistance is evaluated as $\rho_h = 150-200$ Ohm*m value and with the electric field voltage $E = 5 \cdot 10^3\ V/m$ the permissible time of human exposure to electric field t_{don} equals to 8 hours allowing for this condition, having inserted (5) expression into (4), we obtained the numerical value for $W_{h.don}$ in Joules:

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

Field energy disseminates itself in body weight. (6) expression was obtained for the permissible energy absorbed by 71.9 kg human body exposed to an electic field of industrial frequency. Actually, the weight of each particular person differs from the average value, that is why the expression of permissiblre enegy was supplemented with *k* adjustment factor, which is defined as $k = m_h/71.9$, where m_h is the actual weight of a person exposed to electrical field of industrial frequency, and

(7) $$W_{h.don.} = 0,36k \text{, J}$$

The obtained expression (3), taking into consideration the values of conditional probability of injury, as shown in the probit-function table 2 according to [11], allowed calculating the value of probability that the hazard to human safety on the part of electric power, the values of which are set forth in the table, will be implemented.

Table 2. Values of probability of human injury caused by electric energy depending on the probit-function value

		Relative probability of injury Qi, %											
		0	10	20	30	40	50	60	70	80	90	–	99
Probit-function value *Pr*	0	–	3.72	4.16	4.48	4.75	5.00	5.25	5.52	5.84	6.28	0.00	7.33
	1	2.67	3.77	4.19	4.50	4.77	5.03	5.28	5.55	5.88	6.34	0.10	7.37
	2	2.95	3.82	4.23	4.53	4.80	5.05	5.31	5.58	5.92	6.41	0.20	7.41
	3	3.12	3.87	4.26	4.56	4.82	5.08	5.33	5.61	5.95	6.48	0.30	7.46
	4	3.25	3.92	4.29	4.59	4.85	5.10	5.36	5.64	5.99	6.55	0.40	7.51
	5	3.36	3.96	4.33	4.61	4.87	5.13	5.39	5.67	6.04	6.64	0.50	7.58
	6	3.45	4.01	4.36	4.64	4.90	5.15	5.41	5.71	6.08	6.75	0.60	7.65
	7	3.52	4.05	4.39	4.67	4.92	5.18	5.44	5.74	6.13	6.88	0.70	7.75
	8	3.59	4.08	4.42	4.69	4.95	5.20	5.47	5.77	6.18	7.05	0.80	7.88
	9	3.66	4.12	4.45	4.72	4.97	5.23	5.50	5.81	6.23	7.33	0.90	8.09

Let us explain the use of Table 2 on the example. Assume that it is necessary to define the probability of threat to human safety based on the known probit-function value, Pr=5.15. This value corresponds to the interseption of line "50 %" and column "6 %" of Table 1, under which the probability of threat to human safety at electric power units equals to 56 %. Should the probit-function take average values, for example Pr = 5.165, the probability of threat to human safety may be defined using the expression:

(7) $$Q(5,165) = \frac{Q(5,15) + Q(5,18)}{2} = \frac{56\% + 57\%}{2} = 56,5\%.$$

Allocation of working conditions to one or another IF EF harm and danger class should be pursuant to the table 3, depending on the value of excess over maximum permissible level (MPL) of IF EF.

Table 3. Working conditions classes under IF EF, pursuant to [11], and values of working conditions degrees, and their proposed probabilistic description

<table>
<tr><td rowspan="3">Production environment factor</td><td colspan="6">Working conditions class puruant to [11]</td></tr>
<tr><td rowspan="2">Permissible 2</td><td colspan="4">Harmful 3</td><td rowspan="2">Dangerous (extreme) 4</td></tr>
<tr><td>1 degree 3.1</td><td>2 degree 3.2</td><td>3 degree 3.3</td><td>4 degree 3.4</td></tr>
<tr><td rowspan="4">IF electric fields (50 Hz)</td><td>≤ MPL</td><td>≤3</td><td>≤5</td><td>≤10</td><td>> 10</td><td>> 40</td></tr>
<tr><td colspan="6">Values of working conditions degrees, and their proposed probabilistic description</td></tr>
<tr><td>≤ MPL</td><td>1.1–3.0</td><td>3.1–5.0</td><td>5.1–10.0</td><td>10.1–40</td><td>>40</td></tr>
<tr><td></td><td>0.0007-0.04</td><td>0.041-0.083</td><td>0.084-0.2</td><td>0.21-0.53</td><td>0.54-1</td></tr>
</table>

Comparison of consequence levels and probabilities with the consequences known from practice allowed offering the probabilistic description of categories of occupational risk associated with electric power effects: working conditions class one – no risk; class two – permissible risk; class three, degrees: 3.1 – minor risk; 3.2 – low risk; 3.3 – medium risk; 3.4 – high risk; class four – extremely high risk.

According to the table, evaluation of occupational risk associated with IF EF effect lies in determination of risk value and degree, depending on which the frequency and the time of the arrangements and actions aimed at reduction of the risk of electric injury and occupational disease should be scheduled. For instance, with extremely high values of risk of electric injury frequency and occupational disease (0.54-1), safety monitoring should be conducted on a permanent basis and immediate risk mitigation should be provided for. An instance of practical implementation of such solution in EHV electric installations, as per [14, 15], is represented by the method of electrical safety assurance during the works with current-carrying parts of extra-high voltage electrical installations. With high (0.21-0.53) and medium (0.084-0.2) risk values, it is also desirable to exercise permanent control of safety condition, since the risk must be reduced as soon as possible. With low (0.041-0.083) and minor risk values (0.0007-0.04), it should be reduced to permissible levels within the established period, low values requiring no special risk-reduction arrangements, though the risk should still be controlled in respect of particular groups of employees (minors, incapacitated persons and others), who are in need of special protection.

Conclusions

Generated was the graphic-analytical model that interprets the set of conditions of an electrical safety system in high-voltage electric installations, as well as possible transitions between them based on the applicable hygienic classification of working conditions, systemic and risk-oriented approaches allowed developing the proposals on evaluation of occupational disease risk caused by electric power effects using the method of probit-function, as well as the arrangements aimed at minimization of health risk caused by electric power effects to the health of the staff, who interact with EHV electric installations, depending on its probabilistic description.

Thus, with extremely high 0.21-0.53 and medium 0.084-0.2 values of electric injury risk, permanent control of safety condition should be exercised, since the risk must be reduced immediately. With high 0.21-0.53 and medium 0.084-0.2 risk values, it is also desirable to exercise permanent control of safety condition, and the risk should be reduced in a short period. With low (0.041-0.083) and minor risk values (0.0007-0.04), it should be reduced to permissible levels within the established period, low values requiring no special risk-reduction arrangements, though the risk should still be controlled in respect of particular groups of employees (minors, incapacitated persons and others), who are in need of special protection.

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REFERENCES

[1] Perelman L.S., Tihodeev N. N., Morozov J. A., Research of electric field of lines and substations of ultrahigh pressure variable and a direct current, *Energoatomizdat*, NIIPT, (1985), 104-105
[2] Silvester P., Chari M., Finite element solution of saturate magnetic field problems, *IEEE Trans. Power Appar. Syst.*, 89 (1970), n.7, 1642–1651
[3] Dovbysh V. M., Maslov M. Ju, Spodobaev J. M., Electromagnetic safety of elements of power systems: the monographic, *IPK Commonwealth*, (2009), 198-204
[4] Kutin V. M., Stiskal V. M., Methods of calculation of screening devices for substations of extrahigh tension, Technical electrodynamics. *Problems of the modern electrical engineering*, (2010), n.1, 71-74
[5] Miroljubov N. N, Kostenko M. V, Levinshtejn M. L, Tihodeev N. N., Methods of calculation of electric fields, *The Higher school*, (1963), 415-421
[6] Izmerov N.F., Suvorov G.A., Physical of factors industrial and environment. Hygienic of estimation and control, *Medicine*, (2003), 556-561
[7] Pukach A., Teslyuk V., Ivantsiv R. A., Komada P., Method and means of measuring small quantities of electrical resistance, *Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska*, 4 (2012), 14-16
[8] Zyska T., Lozbin V., Analiza możliwości stosowania efektów termoelektrycznych do badań termoogniw, *Przegląd Elektrotechniczny*, 3(2008), 32-34
[9] The electric security. Electric fields of industrial frequency. Permissible levels of intensity and the requirement to monitoring procedure on workplaces: GOST 12.1.002-84, *Standards Publishing House*, (1985), 5-7
[10] State sanitary norms and rule during work with the sources of the electromagnetic fields: DSanPiN 096-2002, *National standard of Ukraine*, (2003)
[11] The state sanitary standards and rules, Hygienic of classification of labor behind indicators of harm and danger of factors of the industrial environment, weight and intensity of labor process, *The Ministry of health protection Ukraine*, 248 (2014)
[12] Bliss C.I., The Method of Probity, *Science*, 79 (1934), 409–410
[13] Belov, P.G., The system analysis and modeling of dangerous processes in and techno sphere, *Akademiya*, (2003), 512-523
[14] Bondarenko E.A., Kutin V.M., Estimation of risk of the electric traumatism by the method it is probability – analysis for management from the electric security, *Power of engineering: Economics, Techniques, Ecology*, 41 (2015), 69–72
[15] Dolin P.A., Osnovi techniki bezopasnosti v electroustanovkakh, *Moscow: Energoatomizdat*, (1984). 484-492