Methodology of fire risk analysis in electrical installations of a production facility

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Abstract. This article lists the principles of fire risk assessment and management of electrical installations, provides the main terms used in this subject area, and their meanings. The article also talks about factors affecting the magnitude of fire risk (risk-forming factors). Special attention is paid to the human factor. Formulas for probabilistic assessment of fire risks of electrical installations and an algorithm for assessing the fire hazard of electrical installations, as well as a scheme of the algorithm for calculating individual fire risk are given.

1. Introduction
Principles of fire risk assessment and management of electrical installations. Let us consider, within the framework of the current regulatory framework [1, 2], the basic concepts related to the term “fire risk” in relation to a certain set of electrical installations of a production facility:
- risk - a combination (product) of the probability of events and their consequences;
- permissible fire risk – its reasonable level, based on the socio-economic conditions of society at the present time;
- individual fire risk, which can lead to the death of a person as a result of exposure to fire hazards;
- social fire risk – the degree of danger leading to the death of a group of people as a result of exposure to fire hazards;
- a safe zone in which people are protected from exposure to fire hazards, or in which there are no dangerous factors;
- explosion - rapid chemical transformation of the medium, accompanied by the release of energy and the formation of compressed gases;
- explosion and fire hazard of the object of protection – the state of the object of protection, characterized by the possibility of fire and explosion;
- fire hazards (risk-forming factors), the impact of which can lead to loss of life, disability, poisoning and material damage;
- fire risk assessment – the process of comparing the real risk with its specified criteria in order to determine the significance;
- fire alarm system – a set of technical means designed to detect and notify of a fire, issue commands to turn on automatic fire extinguishing installations and turn on smoke protection installations;
- fire prevention system – a set of technical means that exclude the possibility of a fire at the protection facility (a protective shutdown device, which is a differential switch for leakage current, the value of which should not exceed 100 mA);
- fire risk management – a system of procedures and methods for managing emerging hazardous situations, identification, analysis, assessment, processing and monitoring of risk-related, to ensure loss reduction;
- fire risk management – an action taken to implement decisions within the framework of risk management;
- fire risk optimization - the procedure for finding the best risk value produced by:
  a) at the design stage – minimizing its value with given material and financial resources;
b) at the operational stage - ensuring an acceptable (regulatory) risk value while minimizing (limiting) financial resources;

- a mathematical model of fire risk is the equivalent of an object that reflects in a formalized form its main dangerous properties in the form of patterns of cause-and-effect relationships.

2. Risk-forming factors of the fire situation and the assessment of the reliability of the "human factor".

The magnitude of fire risk (RI) is influenced by a large number of various factors that characterize both the specifics of the specific operating conditions of a production facility (electrical installations of public and industrial buildings) and the specific features of danger, uncertainty, opportunities in which production activities are carried out [3].

The factors that contribute to the emergence and development of a fire situation at the facility will be called risk-forming factors (RFF). Considering that the number of man-made risk forming factors is quite large, we will limit ourselves to considering the so-called native risk-forming factors that are directly related to the subject area (diagnostics of fire safety of electrical installations).

In the literature sources [4, 5, 6, 7], the risk-forming factors of the human-machine system "Human-Electrical Installation-Environment" are considered, where the role of each component (electrical installation and environment) in the occurrence of dangerous technogenic situations was established. At the same time, it was noted that the technogenic safety of any object is determined by the reliability of its weakest (vulnerable) component, i.e. a person.

The negative impact of a person on the technogenic safety of an object will be denoted by the concept of "human factor", i.e. the totality of socio-economic abilities of a person, the degree of realization of which is due to the motivation and attitude of personnel to the process of work, their moral and material interest in high-performance work. The main manifestation of the negativity of the human factor is the following: a person in the course of his activity for one reason or another may make mistakes of various kinds. The property of a human operator to accurately perform his functions under given conditions of professional activity in time is interpreted as reliability, which is one of the components of professional fitness.

It is also necessary to take into account that in the process of life a person may find himself in an extreme situation when physical and psychological stress reach such levels at which the individual loses the ability to rational actions and decisions adequate to the current situation.

The human factor affects various activities of people, organizations, and economic objects. If the role of operator errors prevails in human-machine systems, then with an increase in the level of development of the social environment, the importance of erroneous organizational and managerial decisions affecting the stability of the functioning and sustainability of relevant organizations increases.

The most common dangerous consequences are human errors – unintentional actions that go beyond the regulated boundaries, or failure to perform the necessary actions. Negative consequences of erroneous actions when working with technical objects are possible if the design does not provide for measures to neutralize them (Table 1) [8].

Table 1 - The main causes of erroneous actions of electrical personnel

| Stages of production activity | List of reasons for ETP errors |
|------------------------------|-------------------------------|
| Maintenance of electrical networks and electrical installations | • Incorrect actions and unintentional mistakes in the production of works... |
| Actions and decisions of the operator | • Errors in operational decisions due to violations of regulations and instructions |
| Major repairs, reconstruction, manufacture of products and accessories | • Malfunction or absence of instruments (measurement and diagnostics) |
| Control of production works and events | • Unclear formulation of the operational task |
| Personnel management, decision-making | • Violation of regulatory requirements |
| Socio-psychological aspects of the "human factor" | • Inattentive inspection of equipment during its acceptance at the end of repair |
|                              | • Unsatisfactory involvement of management in ensuring work safety |
|                              | • Insufficient level of professional training |
|                              | • Indifferent attitude to the condition of the equipment |
|                              | • Deliberate deviation from operating and safety standards |
|                              | • Low motivation of professional behavior of the employee |
|                              | • Weak adaptive characteristics of an employee in extreme situations |
|                              | • Psychological and physical errors |
The reason for the errors lies in the ratio of the capabilities of the personnel under the given conditions of activity and the loads (requirements) on it, which can be quantified using the "load-bearing capacity" model. A person's capabilities are related to his psychophysical characteristics, the degree of professional readiness to perform his functions. The conditions of activity in relation to the normative ones deteriorate with adverse environmental influences and irrational organization of work.

Figure 1 shows the classification of the causes of improper actions of electrical personnel leading to a fire in an electrical installation.

An erroneous decision is an incorrect unintentional execution or non-execution of a series of sequential actions due to an incorrect assessment of the flow of the regulated process. To assess the probability of errors, in particular, the method of personnel error analysis (Human Reliability Analysis - HRA) is used. Analyzing the decision-making process, it is possible to determine the causes of erroneous actions of personnel, which can become events that initiate an accident and the occurrence of a fire.

Quantitative assessment of the risk of electrical installation accidents is complicated by the uncertainties of the reliability characteristics of personnel, as already noted, the weak link of human-machine systems and their protection systems. In recent decades, methods for quantifying the reliability of the human factor have changed significantly compared to those traditionally used in calculating equipment reliability indicators.

![Figure 1 - Classification of the causes of improper actions of electrical personnel](image_url)

The reliability of personnel in the maintenance of electrical installations of a production facility includes the following components [9]:
- psychosomatic, which is provided by training and depends on the properties of memory;
- cognitive, which is provided by the control and restoration of health;
- motivational, depending on the characteristics of the workforce, ensuring the formation of employee motivation.

An attempt to describe the properties of the operator using the mathematical formalism of the processes of hazard identification, development and occurrence of a fire situation is presented in Figure 2.
3. Probabilistic assessment of fire risks of electrical installations.

Fire risk assessment is carried out by comparing the calculated risk values with its normative value established by Federal Law No. 123-FZ “Technical Regulations on Fire Safety requirements” [2].

The calculated values of fire risk are determined on the basis of:

- a) analysis of fire safety of buildings;
- b) determination of the frequency of implementation of fire-hazardous situations;
- c) construction of fields of fire hazards for various scenarios of its development;
- d) assessment of the consequences of exposure of risk-forming factors of fire on people;
- e) availability of fire safety systems of buildings.

The determination of the calculated values consists in assessing the individual fire risk for people. The numerical expression of individual fire risk is the frequency of exposure to fire hazards (OFP) on a person in a building. The list of OFPS is established by Article 9 of the “Technical Regulations”.

Fire hazard conditions of electrical installations at the facility in accordance with GOST 12.1.004-91 are determined by the formula:

\[ Q_f = Q_R + Q_V + Q_P + Q_T \leq 10^{-6} \]  

where:
- \( Q_R \) – the probability of occurrence of a fire-hazardous mode (short circuit, overload, increase in transient resistance, etc.), 1/year;
- \( Q_V \) – the probability that the value of the parameter (current, transient resistance, etc.) lies in the range of fire-hazardous values;
- \( Q_P \) – the probability of failure of the protection device (electrical, thermal, etc.);
- \( Q_T \) – the probability of the combustible material reaching a critical temperature or igniting it.

The data obtained on the estimated probabilities of fire occurrence are compared with the standard value of \( 1 \times 10^{-6} \) per year, which is considered safe if the actual or estimated probability does not exceed the permissible one.

An objective indicator of the fire hazard assessment of electrical installations is the probability of a fire and its consequences (moral losses (loss of life), material and environmental damage. Moreover, this probability should not exceed the normative value.

The probability of fires from electrical installations of the object is determined by the formula:

\[ P = \frac{n}{N} \]  

where \( n \) is the number of fires per year, \( N \) is the number of electrical installations in operation at the facility.
When analyzing the fire situation of an object, it is necessary to evaluate the reliability characteristics of the electrical installation.

Emergency fire-hazardous modes are determined by simulating malfunctions of elements in functional units of electrical equipment. Blocks are identified whose failure leads to the ignition of materials in the immediate vicinity.

The probability of ignition of an electrical installation is determined by the following expression:

\[ Q = [1 - (1 - Q_R)(1 - Q_I)]Q_f, \] (3)

where \( Q_R \) – the probability of a fire, depending on the parameters of the reliability of the elements of the electrical installation of the EI;

\( Q_I \) – the probability of an ignition source arising due to the design features and manufacturing technology of the EI;

\( Q_f \) – the probability of failure of the EI protection device.

Value \( Q_R \) is determined by the formula:

\[ Q_R = 1 - \prod_{i=1}^{n} [1 - P_{R,i}] \approx \sum_{i=1}^{n} P_{R,i}, \] (4)

where \( P_{R,i} \) – the probability of ignition of the EC from a fire-hazardous component element of the i-th type; \( n \) is the number of types of elements. Then the probability of ignition of the product from transistors can be denoted as \( P_{R,1} \), from diodes \( P_{R,2} \), from capacitors \( P_{R,3} \), from transformers \( P_{R,4} \) etc.

Value \( P_{I} \) is defined by the expression:

\[ P_{I} = - \prod_{j=1}^{m} (1 - P_{I,j}) \approx \sum_{j=1}^{m} P_{I,j}, \] (5)

where \( P_{I,j} \) – the probability of occurrence of an ignition source of a type i flammable element; \( m \) is the number of flammable elements of a certain type in an electrical product.

The value of \( P_{f} \) is determined according to the expression:

\[ P_{f} = \lambda_j TP_{EI/k}Q_{f,1/k}Q_{f,2/k}, \] (6)

where \( \lambda_j \) – failure rate of the j-th element of the EI, 1/h;

\( T \) – the average duration of operation of the electrical installation;

\( P_{EI/k} \) – the probability of a short circuit in a fire-hazardous element in case of failure;

\( Q_{f,1/k} \) – the probability of ignition of the j-th element;

\( Q_{f,2/k} \) – the probability of ignition of structural materials located in the immediate vicinity of the EI.

The probability of occurrence of the ignition source of the electrical installation \( Q_R \) is determined by the formula:

\[ Q_R = 1 - \prod_{h=1}^{L} [1 - P_{R,h}] \approx \sum_{h=1}^{L} P_{R,h}, \] (7)

where \( P_{R,h} \) – probability of occurrence of the ignition source of the EI from the k-th type of production failures.

\( L \) – the number of types of failures. Then the probability of the ignition source of the EI from poor-quality solder joints can be denoted as \( P_{R,1} \), from short circuits of conductors \( P_{R,2} \), from conductor breaks \( P_{R,3} \), from violations of the contacts in the connectors \( P_{R,4} \) etc.

Value \( P_{k} \) is determined by the formula:

\[ P_{k} = 1 - \prod_{s=1}^{r} (1 - P_{k,s}) \approx \sum_{s=1}^{r} P_{k,s}, \] (8)

where \( P_{k,s} \) – the probability of occurrence of the ignition source of the EC from the s-th failure according to the k-th type of failure;

\( r \) – number of fire-hazardous failures by type k.

Probabilistic indicators of the occurrence of fire-hazardous failures of electrical installations are given in Table 1.
Table 1. Probabilistic indicators of the occurrence of fire-hazardous failures of electrical installations

| Causes of failures                  | The probability of occurrence of an ignition source for various types of failures $P_{k,ii}$ |
|------------------------------------|------------------------------------------------------------------------------------------------|
| Poor-quality contact connections   | $4.0 \times 10^{-2}$                                                                        |
| Conductor closures                 | $0.19 \times 10^{-2}$                                                                        |
| Conductor breakage                 | $0.08 \times 10^{-2}$                                                                        |
| Destruction of contacts            | $0.7 \times 10^{-2}$                                                                         |
| Other refusals                     | $0.03 \times 10^{-2}$                                                                        |
| Total probability of failure       | $5.02 \times 10^{-2}$                                                                        |

Value $P_{k,ii}$ determined by the formula (2).

The probability of failure of protection is calculated by the following formula:

$$P_{k,ii} = k_1k_2,$$  \hspace{1cm} (9)

where $k_1$ – the coefficient characterizing the protection of the EI from fire-hazardous modes;

$k_2$ – a coefficient that takes into account the presence or absence of a special fire extinguishing system in the EI. If there is such a system, the value $k_2=0.05$, in her absence $k_2=1$.

Value $k_1$ calculated by the formula:

$$k_1 = 1 - \frac{N}{Z},$$  \hspace{1cm} (10)

where $N$ - number of fire-hazardous modes (determined in the process of simulating malfunctions); $Z$ - number of modes in which the EI protection is triggered (determined in the process of simulating malfunctions).

To assess the fire hazard of an electrical installation, it is necessary to develop a test program and methodology that takes into account conductive, insulating and structural elements and materials [10].

The algorithm for assessing the fire hazard of electrical installations is shown in Figure 3.
Calculation of the emergency mode of the electrical load

Conducting experiments on emergency electrical overload

The component element can become an ignition source?

Determination of the parameters of the emergency fire-hazardous electrical mode for the component element

Assessment of the probability of occurrence of an emergency fire-hazardous regime

Conducting tests for flame propagation in the structure

There may be flame propagation in the design?

Calculation of the probability of a fire in the structure

Figure 3 - Algorithm for determining the fire hazard of electrical installations of a production facility

In accordance with Article 93 of the "Technical Regulations", the value of an individual fire risk that can lead to the death of a person as a result of exposure to fire hazards for production facilities should not exceed $1 \times 10^{-6}$. For objects of the social sphere - the value of the individual fire risk is $1 \times 10^{-7}$. 
Figure 4 shows a block diagram of the algorithm for calculating individual fire risk.

**Fire hazard analysis of electrical installations of a production facility**

- Determination of the probability of occurrence of fire-hazardous situations
- Determination of fire risk factors
- Formulation of a mathematical model and modeling of the dynamics of fire development
- Assessment of the consequences of exposure to fire hazards
- Determination of integral fire risk
- Calculation of moral losses associated with the death of people
- Calculation of material and environmental damages
- Calculation of fire risk

The calculated value of the fire risk does not exceed the standard

**Conclusion: the fire risk does not exceed the permissible value**

The calculated value of the fire risk exceeds the standard

**Conclusion: the fire risk exceed the permissible value**

**Figure 4** - Procedure for calculating individual fire risk

**Conclusions**

The state of fire safety of electrical installations of the infrastructure of cities and settlements in Russia poses a threat to national security, which led to the need to include the problem in the List of critical technologies approved by the President of the Russian Federation. The current situation is caused by a complex of problems of an economic, legal and technological nature, among which the most urgent are:

- lack of a unified concept of fire risk management of electrical installations of production facilities;
- lack of effective methods and tools for diagnosing the technical condition of the electrical facilities of the social sphere;
- imperfection of the regulatory legal provision of fire safety and lack of proper control by the supervisory authorities of the Ministry of Emergency Situations and gosgortehnadzor;
- the limited material and financial resources allocated to ensure technogenic safety, which led to significant depreciation (70%) of the fixed assets of electric power facilities.

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