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Original Theoretical Research

Matrix of Fire Hazard Factors for Overhead Power Lines as a Basis for Risk Modeling

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Abstract

Introduction. Studies of fire risks associated with overhead power lines (OHPLs) consider combustible materials, terrain, and meteorological conditions. The mechanisms of fire occurrence and spread have been studied, and quantitative risk modeling is being developed based on incident statistics. However, these scenarios rely on arbitrary or poorly defined sets of initial factors, making it difficult to create unified risk management systems. This scientific work aims to fill this gap by creating a unified classification of fire hazard factors for overhead power lines that takes into account the causes, environment, and development of fires. A scenario-based risk matrix for OHPLs is built on this foundation.

Materials and Methods. The basis of the study was a method for assessing fire risk, which considers fire from overhead power lines as a result of the interaction between three key components: the ignition source, combustible medium and fire propagation conditions. Through an analysis of the relevant literature, these components were broken down, classified, and the principles for systematizing them were identified.

Results. Ignition sources, combustible medium, and fire propagation conditions were presented as axes in the scenario matrix of fire risk associated with overhead power lines. These factors were classified and structured using author-created diagrams. The first one included the types of short circuits, heating, and ignition mechanisms. In the second, four classes of materials were differentiated by their sensitivity to fire. The third one described three categories of fire propagation conditions. The risk level and critical ignition energy were mathematically represented. The final matrix aggregated four classes of material: high-sensitive, medium-sensitive, low-sensitive, and specific. Fire spread conditions were divided into favorable, moderate, and unfavorable. Taking into account the ignition sources (interphase and single-phase), the risk levels were determined: low, medium, high, and critical.

Discussion. The matrix combined 24 typical scenarios of the studied hazard (two groups of sources × four classes of materials × three categories of propagation conditions). Five scenarios (approximately 21%) were critical. As a rule, they occurred with a combination of high-energy emergency conditions, high- and medium-sensitive materials and adverse weather conditions. The matrix can be used in the transition from a qualitative description of OHPLs to a quantitative assessment of the probability of a fire and its consequences. This innovation will be beneficial for modeling OHPL incidents, refining safety measures, and improving risk assessment. Scenarios can be ranked based on importance, allowing for a more efficient allocation of resources for protective measures.

Conclusion. The new approach, in contrast to the traditional one, makes it possible to overcome the limitations of the fragmented hazard assessment and systematically analyze fire scenarios related to overhead power lines. This allows us to justify decisions on modernizing and strengthening the protection of individual network sections, i.e., to focus investments on infrastructure elements and typical situations that fire risks depend on to a greater extent. Future research in this area is expected to:
– supplement accident statistics and the amount of experimental data on the energy characteristics of ignition sources;
– provide a quantitative parameterization of the function that represents the risk level for each scenario;
– set numerical thresholds for four risk levels.

Keywords: overhead power line, OHPL, ignition source, flammable environment, fire propagation conditions, OHPL fire risk matrix

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Оригинальное теоретическое исследование

Матрица факторов пожарной опасности воздушных линий электропередачи как основа для моделирования риска

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Аннотация

Введение. Исследования пожарных рисков, связанных с воздушными линиями электропередачи (ВЛЭП), учитывают горючие материалы, рельеф и метеорологические условия. Изучены механизмы возникновения и распространения пожаров. На базе статистики инцидентов развивается количественное моделирование рисков. Однако сценарии опираются на произвольные или слабо формализованные наборы исходных факторов, что затрудняет формирование единых систем управления рисками. Представленная научная работа восполняет этот пробел. Ее цель — создание единой классификации факторов пожарной опасности ВЛЭП с учетом причины, среды и развития горения. На этой базе строится сценарная матрица риска для ВЛЭП.

Материалы и методы. Основа исследования — метод оценки пожарной опасности, при котором пожар от ВЛЭП рассматривается как результат взаимодействия трех ключевых компонентов: источника зажигания, горючей среды и условий распространения горения. Анализ литературы позволил провести декомпозицию этих элементов системы, классифицировать их и определить принципы систематизации.

Результаты исследования. Источники зажигания, горючая среда и условия распространения горения показаны как оси сценарной матрицы риска пожаров, связанных с ВЛЭП. Факторы классифицируются, структурируются и приводятся в виде авторских схем. Первая включает типы замыканий, нагрева и механизмы зажигания. Во второй четыре класса материалов дифференцируются по чувствительности к возгоранию. В третьей характеризуются три категории условий распространения огня. Математически представлены уровень риска и критическая энергия зажигания. Итоговая матрица агрегирует четыре класса материалов: высокочувствительные, среднечувствительные, слабочувствительные и специфичные. Условия распространения горения делятся на благоприятные, умеренные и неблагоприятные. С учетом источников зажигания (межфазные и однофазные) определяются уровни риска: низкий, средний, высокий и критический.

Обсуждение. Матрица объединила 24 типовых сценария исследуемой опасности (две группы источников × четыре класса материалов × три категории условий распространения). Пять сценариев (примерно 21%) — критические. Как правило, они возникают при сочетании высокоэнергетических аварийных режимов, высоко- и среднечувствительных материалов и неблагоприятных метеоусловий. Матрицу можно задействовать при переходе от качественного описания обстановки на ВЛЭП к количественной оценке вероятности пожара и его последствий. Новация будет полезна при моделировании инцидентов на ВЛЭП, доработке мер безопасности, улучшении оценки рисков. Сценарии можно ранжировать по значимости, что позволит более рационально распределять ресурсы на защитные мероприятия.

Заключение. Новый подход, в отличие от традиционного, позволяет преодолеть ограничения фрагментарной оценки опасности и системно анализировать сценарии пожаров, связанных с ВЛЭП. Благодаря этому можно обосновать решения по модернизации и усилению защиты отдельных участков сети, то есть ориентировать инвестиции на элементы инфраструктуры и типовые ситуации, от которых в большей степени зависят пожарные риски. В будущих исследованиях по этой теме предполагается:

– дополнить статистику аварий и объем экспериментальных данных по энергетическим характеристикам источников зажигания;
– представить количественную параметризацию функции, которая представляет уровень риска для каждого сценария;
– установить численные пороги для четырех уровней риска.

Ключевые слова: воздушная линия электропередачи, ВЛЭП, источник зажигания, горючая среда, условия распространения горения, матрица риска возгорания ВЛЭП

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Introduction. For a long time, the issues of assessing and reducing fire risk for long linear electric grid infrastructure facilities, in particular overhead power lines (OHPLs), have been in the focus of researchers' attention. The urgency of the problem is due to the frequency and scale of wildfires. In addition, violation of the integrity of power lines is one of the basic vulnerabilities of power systems [1]. In this case, combustible materials, terrain, and meteorological conditions form a complex of dangerous factors that should be considered in detail, separately from the general models of landscape fires.

Abroad, in fire-prone regions, energy companies are forced to use preventive shutdowns [2] and other restrictions (including PSPS[1]), as well as promptly modernize infrastructure to reduce the probabilities of fires [3].

According to the Federal Forestry Agency, 132 fires[2] broke out in Russia in 2019 due to linear-type facilities (including power lines). In the first half of 2023, in the Far Eastern Federal District, the transition from linear-type facilities was identified as an independent cause of 6.2% of the number of fires (3.4% by area)[3].

During the fire-hazardous period (April – October) in 2018, 648 forest fires were registered in the Chelyabinsk region. Of these, 19 (2.9%) were connected to power lines [4].

Landscape fires often occur due to short circuits on power lines and spread rapidly due to heat and strong winds. Such a case was recorded by the Aerial Forest Protection in the Ust-Donetsk region of the Rostov region (a fire on agricultural land on August 15, 2022[4]).

The issues of fire safety of overhead power lines are addressed from several angles. Firstly, the mechanisms of fire initiation and propagation near power lines are actively studied. This includes considering the influence of tower design, wire and insulator characteristics [5], as well as operating conditions [6]. Secondly, weather and climatic factors that contribute to fire occurrence and intensity (high air temperatures, low humidity, strong winds, prolonged periods without precipitation) are assessed [7], along with their interaction with topography and vegetation cover [8]. Thirdly, quantitative risk assessment is developed, based on accident statistics [9]. This involves using probabilistic methods, scenario analysis, and various approaches for ranking overhead line sections by risk level [10].

In the domestic and international literature, various groups of risk factors have been identified. Ignition sources near overhead power lines have been classified and detailed, including:

– equipment defects,
– external mechanical influences,
– atmospheric phenomena,
– human factor.

Various approaches to fire hazard assessment of vegetation cover have been developed and applied. These include the index of burnability, phytomass, and degree of desiccation, among others [11]. In addition, models have been proposed that take into account the influence of terrain, woodlands, fire barrier lines, and distance to infrastructure facilities and settlements [12]. However, these and other factors are usually considered separately within the framework of specific tasks (for example, building fire hazard maps, predicting the spread of fire, or planning clearing measures), without integration them into a single system “ignition source (or initiating action) – combustible environment –fire spread conditions” (IS – CE – FSC).

A separate area of research relates to predicting the development of fire-hazardous situations along overhead power lines [13]. In such studies, a limited number of typical scenarios are usually identified, for which the probabilities of occurrence and possible consequences are analyzed. Examples include fires under wires when trees fall, fires from sparking on towers in conditions of high vegetation dryness, the spread of crown fires through clearings, etc. Scenario matrices, risk maps, and other visualization tools are used to aid management decisions in these cases. However, these scenario descriptions are often based on arbitrary or poorly formalized initial factors, making it difficult to compare and integrate them into unified risk management systems at the energy system or regional level.

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[1] Public safety power shutoff.

[2] *An Up-to-Date Summary of the Fire-Prone Period: 98 Percent of Forest Fires are Caused by Humans.* (In Russ.) URL: https://rosleshoz.gov.ru/news/federal/aktualnaya-svodka-pozharoopasnogo-perioda-98-protsentov-lesnykh-vozgoraniy-voznikayut-po-vine-cheloveka-n4696 (accessed: 18.12.2025).

[3] *Analysis of the Causes of Forest Fires in the Far Eastern Federal District.* (In Russ.) URL: https://rosleshoz.gov.ru/news/dfo/analiz-prichin-vozniknoveniya-lesnykh-pozharov-na-territorii-dalnevostochnogo-federalnogo-okruga-dfo-22041 (accessed: 18.12.2025).

[4] *A Forest Fire in the Ust-Donetsk Region of the Rostov Region Arose from a Landscape Fire on Agricultural Land.* (In Russ.) URL: https://aviales.ru/popup.aspx?news=7474 (accessed: 18.12.2025).

Thus, with a significant amount of empirical data, private classifications and models in the public domain, there is no single systematic classification of the factors determining the fire hazard of overhead power lines. The relevance of such a system, built in accordance with a three-component structure (IS – CE – FSC) and initially oriented towards the use in scenario analysis, is evident. Additionally, a standardized approach to creating a risk matrix for scenarios has not yet been established, in which IS, CE, and FSC would be presented as a set of typical factors reflecting the most likely and hazardous situations. Meanwhile, elements of classification, scenario description, and quantitative modeling remain fragmented and dispersed in the literature. The authors focus on, for example:

– ignition sources [14],

– characteristics of the combustible medium [15],

– fire spread conditions [16],

– methods of probabilistic assessment and ranking of OHPL sections [17].

At the same time, there is no holistic methodological framework that includes the classification of factors, the logic behind their combination in a given scenario, and the relationship between scenarios and a quantitative risk assessment. This scientific work aims to fill this gap by creating a unified classification of factors that affect the fire hazard of overhead power lines. The classification is described in terms of the initiating effects, the combustible environment, and the conditions for fire development. Another innovation of the proposed solution is the construction of a formalized scenario risk matrix for power line sections. To achieve this goal, several tasks were completed:

– analysis of approaches to the description and classification of fire risk factors (mainly near overhead lines);

– classification of factors into three groups (IS, CE, FSC) with an indication of their interactions;

– identification of parameters and classification of the combustible environment in the area of potential exposure to the ignition source;

– definition and classification of ignition and fire spread conditions (FSC);

– generalization of classification results into a limited number of representative states;

– creation of a scenario risk matrix.

Materials and Methods. The basis of this research is the method of fire hazard assessment. In this approach, the occurrence of a fire caused by OHPLs is considered as a result of the interaction between three key components: IS, CE, and FSC. This is a generally accepted approach to assessing complex threats. Thus, multi-criteria solutions are used to determine the reliability of power lines under conditions of multiple natural disasters. For example, methods of hierarchy analysis and entropy weighting coefficients (AHP[5] – EWM[6]) [18]. Another example of a complex methodology is TOPSIS[7]. This approach is applied primarily to the ranking of risks that various types of natural disasters pose to power transmission lines. Let us mention that the method is useful for resource management based on statistics of consequences, rather than causes [9].

The methodology of the work consisted in the sequential decomposition and classification of the components mentioned above. The key principles of systematization have been identified for groups of factors.

For ignition sources, the classification was based on the analysis of their physical nature, causes of occurrence, and aggregated by key physical mechanisms of thermal effects on the combustible environment.

The classification for the combustible medium was based on its pyrological properties and location relative to the structural elements of the overhead line.

The concept of the “fire behavior triangle”, recognized in world pyrology, was used to determine the conditions of fire spread. This article focuses on weather, topography, and characteristics of combustible materials.

Results. To achieve the goal of the study, a literature review was conducted, which allowed us to organize and present the findings in the form of author-created classification schemes for ignition sources, combustible environments, and fire spread conditions. Each of these factors became the axis of the final scenario risk matrix.

Ignition sources classification. Let us mention the variety of causes of fires associated with overhead power lines. These include violations of the rules of operation of electrical networks (wear and tear, human factors) and probabilistic phenomena (climatic conditions). However, for quantitative risk modeling, the root causes of events (for example, a falling tree or a breakdown of an insulator) are less important than the physical characteristics of the ignition process itself. Therefore, from a scientific point of view, a system based on the dominance of physical heat transfer mechanisms and the nature of energy effects is considered to be of better quality.

In the proposed classification, ignition sources belong to one of two classes corresponding to emergency modes of operation. It concerns short circuits between phases (SCPs) and single-phase line-to-ground short circuits (LGSCs). Other types of emergency modes of operation (overloads or unbalanced modes) usually lead to distributed heating of conductors along their entire length, rather than concentrated and high-temperature energy release at one point, which is sufficient to ignite combustible materials.

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[5] analytical hierarchy process.

[6] entropy weighting coefficient method.

[7] technique for order preference by similarity to ideal solution.

This classification makes it possible to clearly distinguish ignition sources by type and heating mechanism (Fig. 1).

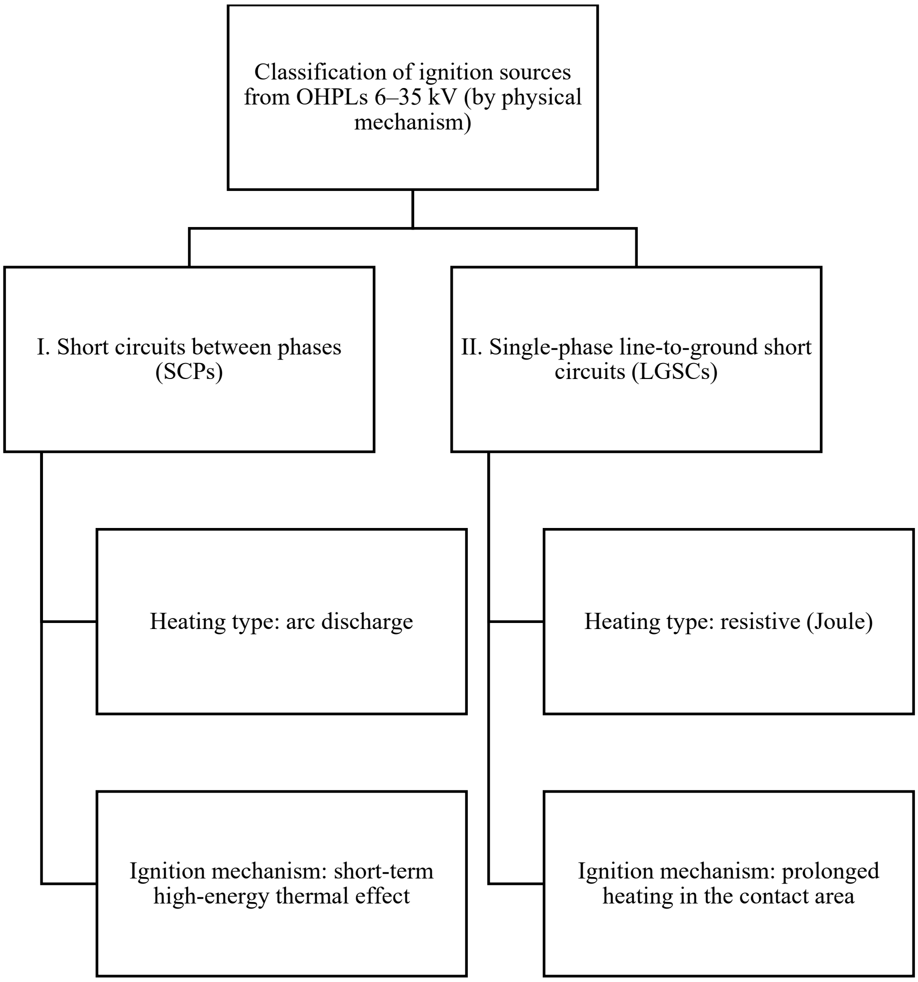

Fig. 1. Classification of fire hazard sources of overhead power lines

I. Short circuits between phases occur under the following circumstances:

- wires colliding due to wind,
- wires icing,
- trees and other objects falling on wires.

In such cases, intense heating is recorded up to 4,000–10,000°C and above. The current strength increases dramatically by 10–100 times compared to the rated mode [7]. In this case, an electric arc is formed — a plasma channel with high temperature and intense heat generation. A short-term but extremely powerful release of energy generates secondary ignition sources — incandescent metal droplets. This circumstance causes a high probability of ignition of dry forest floor or grass.

The risk of wire snapping in high winds can be quantified using models based on nonlinear equations of conductor oscillations. Such systems make it possible to determine the probability of a dangerous phase convergence in real time [8].

At the same time, the level of fire hazard directly depends on current strength and short circuit duration: low, medium or high [5]. Experimental studies confirm that there are specific ranges of fire-hazardous short-circuit currents for non-insulated aluminum wires. Thus, a wire with a cross-section of 25 mm^2 corresponds to a range of 120–180 A [13]. The same class includes double line to ground faults (DLGFs) that occur when wires of two or three different phases fall to the ground. Despite the fact that the current goes through the ground, this mode is electrotechnically equivalent to a short circuit between phases, as it is characterized by high short-circuit currents. The physics of ignition in this mode is identical to SCP: powerful electric arcs occur at the points of contact of the wires with the ground. As a result, the metal melts, and the red-hot droplets ignite combustible materials.

II. Line-to-ground short circuits cause a stable thermochemical effect on combustible materials. This is the most common and main cause of fires. The emergency mode is characterized by prolonged and, as a rule, uncontrolled release of thermal energy.

In 6–35 kV networks operating with an isulated neutral, the LGSC currents are insignificant (usually up to 10 A) [6]. They do not cause instant destruction of elements and equipment, which makes it possible to operate the network in emergency mode for a long time (several hours) without power cuts. During this time, damage is detected and repaired.

This class combines all scenarios in which the conductor of an overhead power line (OHPL) comes into prolonged contact with a grounded combustible object.

There are two types of ground faults in the literature [14]. The first one is metal. We are talking about cases of direct connection of conductors to the ground with negligible resistance at the point of contact. For example:

– wire breakage and fall on the crossarm,

– fall on the transformer substation housing and other metal objects in the protected area of the power line.

Short circuits due to high transient resistance (second type) occur when wires fall on dry grass, as well as if a broken wire touches a tree or wooden support. The same type includes contact through a damaged or contaminated insulator.

The mechanism of thermal action at the phase contact point is the same for both types of LGSCs. At the point of contact with the ground, resistive (Joule) heating occurs due to the passage of a capacitive short-circuit current through a transient resistance at the point of contact. This process is slower than in resistively compensated networks because there is no high-energy arc discharge. Nevertheless, the resulting conductive heat transfer from the heated conductor to the surrounding combustible materials ensures their gradual heating to the ignition temperature, i.e. causes the risk of fire. The earth fault current near the damage site creates local heating zones, which also contributes to the occurrence of a fire. In this case, heat dissipation is determined by the product of the square of the current and the resistance according to the Joule–Lenz law.

For metal circuits, typical transient resistance values range from 0.1 to 10 ohms, whereas for high-resistance circuits, such as when a wire falls on dry grass or contacts wood, the resistance can reach hundreds or even thousands of ohms. With relatively small LGSC currents, the level of transient resistance becomes the main factor determining heat dissipation. When the resistance increases by hundreds of times, the heating power also increases proportionally, creating local zones of intense heat that can ignite combustible materials, even at moderate short-circuit currents.

Thus, the entire variety of root causes has been grouped into two typical physical mechanisms, which will become the first dimension (axis) in the final scenario risk matrix.

Combustible environment (CE) classification. As it has been established earlier, one of the three mandatory fire conditions during the operation of overhead power lines is a combustible environment (CE). This is a combination of:

– combustible materials of natural and anthropogenic nature within the protected overhead line zone;

– overhead line structural elements that can ignite from thermoelectric ignition sources.

When quantifying the probability of ignition, we take into account the key pyrological parameters that determine the sensitivity to ignition. Thus, the minimum critical ignition energy Q_{ign}, which is determined by the heat balance equation, directly depends on the type and moisture content of the combustible material:

$$Q_{ign} = m \cdot c_p \cdot \left(T_{ign} - T_0\right) + m_{moist} \cdot L_{evap}, \tag{1}$$

where m — mass of the heated material, kg; c_p — heat capacity of combustible materials, kJ/(kg·K); T_{ign} — ignition temperature; T_0 — initial temperature; m_{moist} — moisture mass in the material, kg; L_{evap} — heat of water evaporation.

As the moisture content increases, the ignition energy conditions increase significantly. Experimental studies show that with an increase in the humidity of natural combustible materials (NCMs) from 10% to 30%, the required minimum thermal load increases from 20 kW/m^2 to 35–40 kW/m^2, which corresponds to an increase in the critical ignition energy by about 1.75–2 times [15].

An additional factor contributing to the increase in the energy barrier is the energy expenditure on moisture evaporation. The specific heat of evaporation for water is 2.26 MJ/kg. For living vegetation with moisture content of 100–300% relative to dry mass, ignition does not occur at heat fluxes below 35 kW/m^2.

Thus, when compared to dry finely dispersed materials (moisture content 10–15%), the ignition energy barrier for moistened and living NCMs increases approximately 3–10 times, which is consistent with experimental data on the effect of moisture content on the flammability of plant materials [16].

Based on this information, a classification of the combustible medium can be proposed (Fig. 2).

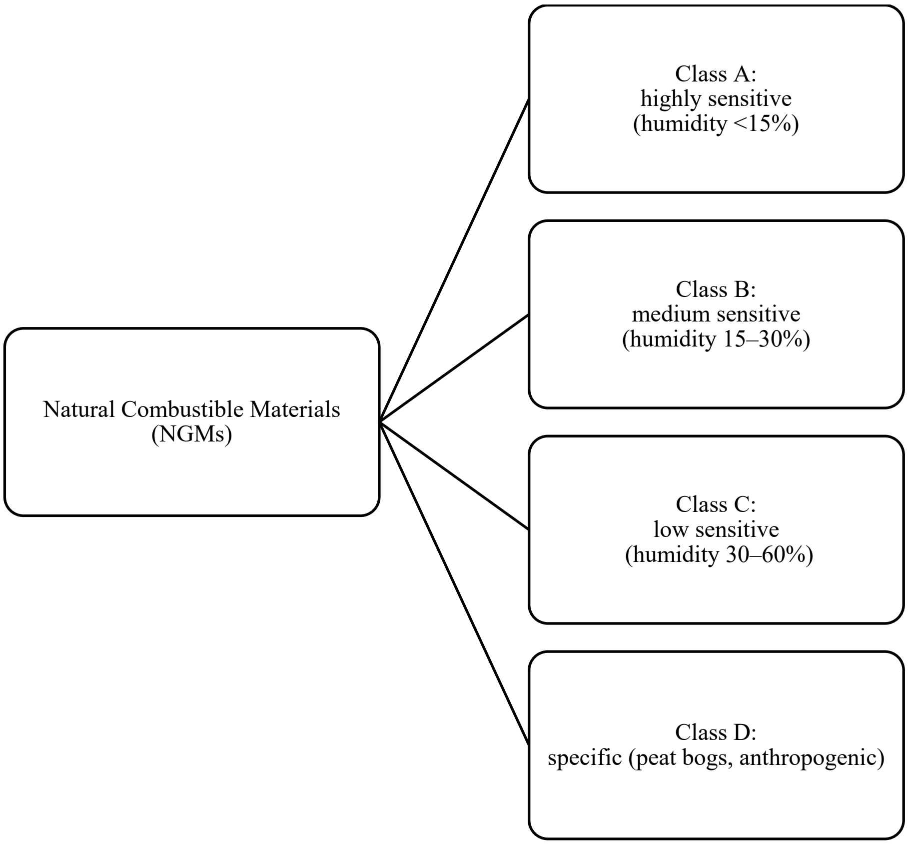

Fig. 2. Classification of combustible materials in OHPL area

Class A. Highly sensitive NCMs. This class is characterized by minimum moisture content (less than 15%) and, as a result, low critical ignition energy (less than 1 kJ). This group includes the most fire-hazardous materials: dry grass and needles (fallen this year), mosses during prolonged drought, as well as organic accumulations on insulators (droppings, down) and materials from bird nests.

Class B. Medium sensitive NCMs. This class combines materials with a moderate moisture content (15–30%), which increases the required ignition energy to 1–10 kJ. Examples: forest floor with moderate humidity, long-fallen needles from previous years, dry branches up to 5 cm in diameter, and support wood with a humidity of 20–30%.

Class B. Low sensitive NCMs. They contain 30–60% moisture. According to equation (1), in this case, high energy (10–50 kJ) is needed for ignition. Low sensitive NCMs are moist forest litter, live needles and foliage in tree crowns, coniferous undergrowth and support wood with a humidity of 30–50%.

Class G. Specific combustible materials. The fire hazard of peat bogs, structural wood, and combustible debris is determined not only by the moisture content (as in classes A, B, and C), but also by specific properties: structural features, chemical composition, and the ability to self-sustaining combustion.

The elements of this class are qualitatively heterogeneous and demonstrate high susceptibility to thermal effects — prolonged during LGSC and short-term from drops of red-hot metal. This is due either to the low ignition energy (flame retardant-soaked wood, dry debris), or the ability to self-sustaining combustion after ignition (peat bogs). As a result, despite the heterogeneity, such materials are taken together for the purposes of scenario risk modeling.

This classification, based on pyrological properties and sensitivity to thermoelectric influences, allows us to move from the generalized concept of “combustible environment” to four classes. This is necessary to build a scenario risk matrix and allows you to quantify the probability of ignition (P_{ign}) in various emergency modes, depending on the current state of CE

Fire spread condition (FSC) classification. Let us consider the situation with such an initial event as the occurrence of a fire from an overhead power line. The damage and the scale of the consequences are determined by the fire spread from the source. The conditions that regulate this process form the third key component of the fire hazard system.

In the framework of this study, the FSC is understood as a set of environmental factors that determine the speed, intensity, trajectory of the fire front and the possibility of its transition between different tiers of the combustible environment. It is important to note that the probability of ignition and spread of fire depends on a number of factors (for example, wind, and humidity). However, in this section they are considered from the point of view of the impact on an existing, developing fire. The FSC classification is necessary for modeling fire scenarios and assessing potential damage.

A model called the triangle of fire behavior is widely used in pyrology. Within the framework of the presented study, the concept is adopted according to which the nature and dynamics of fire spread are determined by the interaction of three groups of factors: weather conditions, topography and characteristics of combustible materials [11]. This takes into account:

– wind speed and air humidity,
– ground form,
– volume of combustible material, its horizontal and vertical location (Fig. 3).

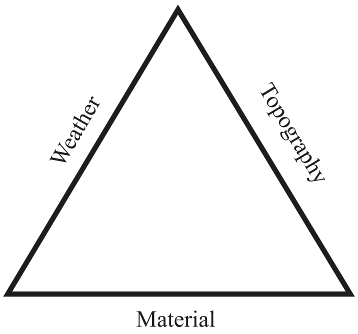

Fig. 3. Fire behavior triangle

For a specific section of overhead line, the topography is taken into account during the design and does not require inclusion in the scenario matrix as a variable. For critical areas (steep slopes), increasing risk factors are used. The characteristics of the materials are also reflected in the classification of the combustible medium:

– Class A materials ensure a high rate of grass-roots fires,
– Class B materials form a “ladder” for crown fires.

Only the weather is changing dynamically, and it requires an operational assessment. Wind and humidity have the maximum predictive potential and are easy to measure.

The fire hazard class (FHC) according to weather conditions is an integral indicator. In Russia, the Nesterov complex indicator is used with a gradation from I (absence of danger) to V (extreme danger). FHC is directly related to the moisture content of small combustible materials. Thus, with FHC V, humidity decreases to 10–15% (class A of the combustible environment), with FHC III, it is 20–30% (class B).

Wind speed of about 10 m:

– increases the probability of emergency modes (whipping of wires at SCP, contact with vegetation at LGSC);
– increases heat generation during ignition;
– determines the velocity of the front during propagation.

Wind speed is a consistently measured and predicted parameter. A threshold value of 5 m/s has been set for scenario analysis. Below this indicator, the fire spreads due to radiation heating at a moderate rate. The higher velocity causes convective heat transfer with flame tilt, spark transfer, and secondary foci [12].

Thus, the system of factors of the fire behavior triangle is reduced to two key dynamic parameters — FHC and wind speed. This reduction is justified physically, statistically and practically.

The fire hazard class (FHC) according to weather conditions determines the pyrological readiness of natural combustible materials. This integral characteristic reflects their ability to ignite and maintain fire. It depends on the type of material, its moisture content and thermal properties.

The wind speed, in turn, determines the dynamics of flame propagation and the formation of secondary foci.

From a statistical point of view, both parameters are reliable indicators of fire danger, and from a practical point of view, their use is justified by the high availability and predictive reliability of meteorological observations.

The FHC and wind speed determine the nature of fie spread conditions (FSCs) for the scenario matrix (Fig. 4).

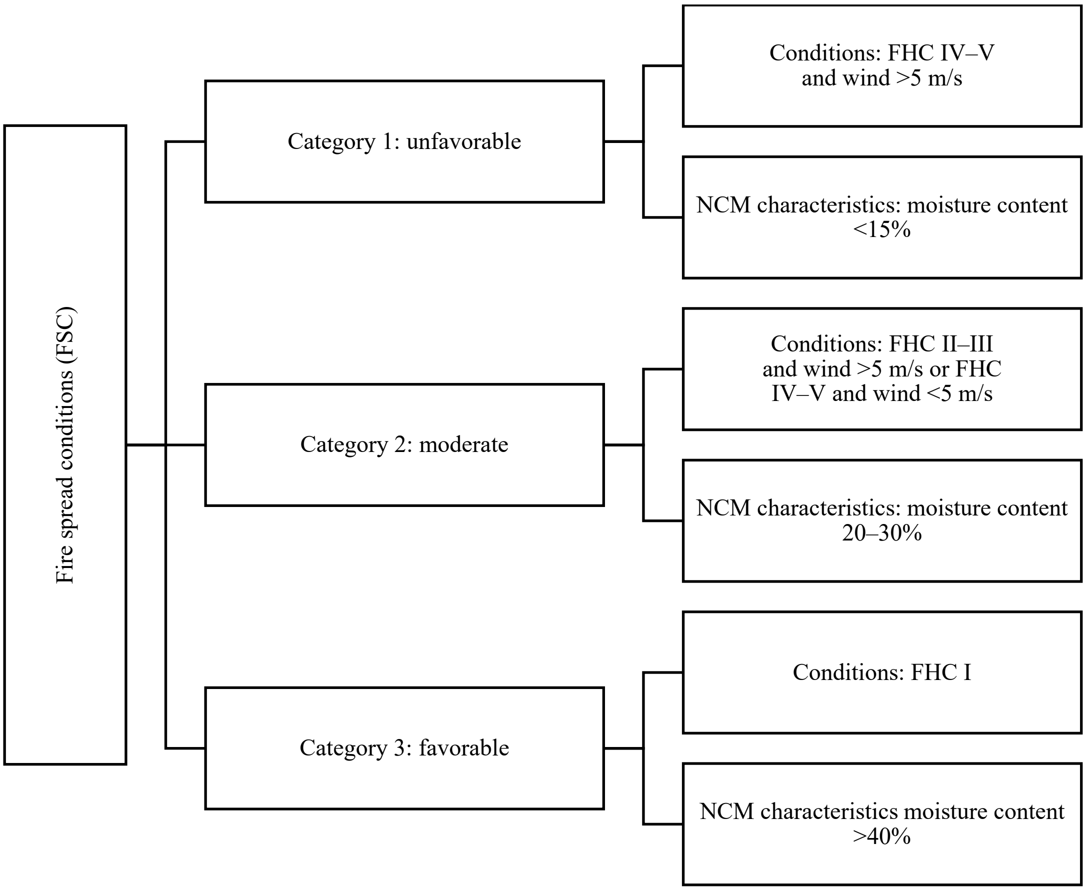

Fig. 4. Fire spread conditions

Fire spread conditions can be described as favorable, unfavorable, or moderate, and the level of threat can be low, medium, or high.

Fire risk scenario matrix. A scale of risk levels is needed to quantify each fire hazard scenario for OHPLs. The analysis of risk assessment methods became the basis for the proposed four-level classification.

Low risk *(R*1*)*. The probability of ignition is minimal or there are no conditions for the development of a fire. It is typical for combinations of: weak ignition sources + CE with high moisture content + unfavorable FSCs (FHC I–II, lack of wind).

Average risk *(R*2*)*. Moderate risk of ignition and limited potential for fire spread. It is typical for combustible materials with moderate pyrological readiness (class B), transitional weather conditions corresponding to FHC III, with wind speeds up to 5 m/s.

High risk *(R*3*)*. High probability of ignition and significant potential for fire spread. It is formed at FHC IV–V and (or) wind speeds of more than 5 m/s in combination with combustible materials of high or moderate pyrological readiness (classes A, B) and ignition sources of increased energy capacity.

Critical risk (*R*4). Maximum risk of ignition and rapid fire development. The risk is generated by powerful ignition sources (SCP, LGSC arcs) in combination with dry fine materials under extreme weather conditions (FHC V, wind >5 m/s).

Risk level *R* for each scenario can be represented as function *f*. It determines qualitative correspondence of input parameters and risk categories *R*1–*R*4 based on an expert assessment of two parameters:

$$R = f\left(P_{\text{вз}}, T_{\text{п}}\right). \tag{2}$$

Here $P_{\text{вз}}$ — probability of catching fire, determined by a combination of IS type and CE class. $T_{\text{П}}$ — severity of consequences. It is determined by the CE class and the FSC category. The speed and scale of distribution are taken into account.

In this paper, the risk levels are qualitatively determined by the characteristics established in the previous sections. The quantitative parameterization of function (2) and the establishment of numerical thresholds for risk levels R1–R4 are the subject of further research.

The above analysis of the three key components (IS, CE and FSC) allows us to form a final scenario matrix (Table 1).

Table 1

Fire risk matrix

IS	Material class	Fire spread conditions		
		Favorable	Moderate	Unfavorable
LGSC	A. Highly sensitive	$R2$ — average	$R3$ — high	$R4$ — critical
	B. Medium sensitive	$R1$ — low	$R2$ — average	$R3$ — high
	C. Low sensitive	$R1$ — low	$R1$ — low	$R2$ — average
	D. Specific	$R2$ — average	$R2$ — average	$R3$ — high
SCP	A. Highly sensitive	$R3$ — high	$R4$ — critical	$R4$ — critical
	B. Medium sensitive	$R2$ — average	$R3$ — high	$R4$ — critical
	C. Low sensitive	$R1$ — low	$R2$ — average	$R3$ — high
	D. Specific	$R2$ — average	$R3$ — high	$R4$ — critical

Discussion. The matrix combined all 24 typical scenarios of fire hazard (two groups of ignition sources × four classes of combustible materials × three categories of fire conditions). The principles of assigning risk levels in the scenario matrix are provided below.

Class D of combustible materials in all scenarios is characterized by the minimum allowable risk level $R2$, even under favorable conditions of fire spreading. Assigning the $R1$ level in this case is impractical for the following reasons:

– the specific properties of such materials, including the ability to smolder and low humidity of structural and flame retardant-impregnated wood,

– the presence of combustible debris prone to sustained combustion.

SCPs with higher thermal impact energy tend to increase the risk level by one category compared to LGSCs with the same class of combustible materials.

Unfavorable fire spread conditions (FHC IV–V at wind speeds of more than 5 m/s) in combination with Class A combustible materials in all cases form critical $R4$ risk level regardless of the type of ignition source.

Approximately 21% of the total number of scenarios are critical ($R4$). They are formed mainly by the following combinations:

– high-energy emergency modes (interphase faults and individual single–phase scenarios),

– highly sensitive and medium-sensitive combustible materials,

– adverse weather conditions.

As you can see, the matrix is a solution that provides a transition from a qualitative description of the situation on the overhead line to a subsequent quantitative assessment of the probability of a fire and its consequences.

Let us list practical application options for this matrix:

– modeling the occurrence and spread of fires on OHPLs,

– refinement of safety measures for specific sections of the network,

– improvement of fire risk assessment in electrical networks.

The matrix allows you not only to identify the presence of increased danger, but also to rank scenarios by importance, which opens up the possibility of a more rational allocation of resources for protective measures.

Conclusion. The main physical and spatial factors determining the fire hazard of overhead power lines are highlighted. Based on them, classifications of ignition sources, combustible environment and fire spread conditions have been developed, reflecting the features of the linear infrastructure and the surrounding area.

The key result of this study is the creation of a risk matrix of 24 scenarios for the occurrence and development of fire on overhead power lines. Unlike the traditional approach focused on the analysis of individual factors, the proposed solution takes into account the interaction of ignition sources, combustible environment and fire spread conditions. The research results allow us to move from a fragmentary assessment of fire hazard to a systematic analysis of specific scenarios. Thanks to this approach, it is possible to justify decisions to modernize and strengthen the protection of individual sections of the network. This makes it possible to focus investments on infrastructure elements and typical situations, on which fire risks depend to a greater extent [10].

Let us note that the results require further development. There are certain limitations associated with an expert assessment of the relative importance of scenarios, which affect the objectivity of assigning risk levels. The lack of accident statistics and experimental data on the energy characteristics of ignition sources prevent a full-fledged quantitative parameterization of scenarios. Overcoming these limitations is a priority area for future research, including the collection and analysis of incident statistics.

In addition, in the future, we will need to develop function *f* that represents risk level *R* for each scenario. Specifically, we plan to quantify the parameters of the function and set numerical thresholds for the four risk levels discussed in this article

A separate area of development for overhead line fire safety systems is the rapid detection of fires. In this context, it is promising to combine a scenario-based approach to risk assessment with neural network computer vision technologies designed to detect smoke and flames in real time [19].

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