



National Technical University
"Kharkiv Polytechnic Institute"

PROTECTION OF OVERHEAD POWER LINES 6-35 KV WITH PROTECTED WIRES AGAINST DIRECT LIGHTNING STRIKES

Shevchenko S., Danylchenko D., Dryvetskyi S.

Danylchenko D.O., Dryvetskyi S.I., Shevchenko S.Yu.

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The team of authors:

Danylchenko D.O., Dryvetskyi S.I., Shevchenko S.Yu.

Reviewers:

Miroshnyk O.O., Shabatura Yu.V., Krivonosov V.E.

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Abstract. *The monograph is devoted to the solution of an actual scientific and applied problem in the field of lightning protection of overhead power lines with protected wires of medium voltage classes from direct lightning strikes. The paper experimentally proved that protected wires are less likely to be affected by direct lightning strikes than non-insulated wires. This is due to the protective sheath of the protected wires, since the conditions for the occurrence of an oncoming conductor become much more complicated, and the area of lightning capture is significantly reduced. Current methods of calculating the number of direct lightning strikes do not take into account the type of wire on overhead lines, which leads to incorrect calculations of the number of direct lightning strikes and, as a result, the number of line shutdowns. The obtained results made it possible to create a new approach to lightning protection of overhead lines with protected wires, to create a combined power transmission line. This line contains in its design protected wires and a non-insulated wire, which performs the role of a lightning protection wire. The created model of the combined line was tested experimentally, not a single lightning strike to the protected wires was recorded.*

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INTRODUCTION

The quality of providing consumers with electricity directly depends on the reliability of distribution power networks, which are a key link in the power supply system. In order to increase the efficiency, technical level and safety of distribution networks, it is necessary to use scientifically based technical solutions and technologies in matters of electric energy transmission by overhead power lines. In industrialized countries, protected wires (PPL) are widely used on overhead lines of medium voltage classes of 6 - 69 kV, which have significant advantages over lines with non-insulated wires.

In recent years, there has been a significant increase in lightning activity on the planet and on the territory of Ukraine in particular. This leads to more frequent damage to electric power facilities, including overhead power lines of all classes of nominal voltage. With the beginning of the mass use of 6 - 35kV shielded wires on distribution substations, there was a need to take mandatory technical measures for their lightning protection.

The peculiarity of the lightning protection problem of the lightning protection system is that for the 6 - 35 kV network, a single-phase short circuit to the ground is not an emergency situation and is not subject to mandatory shutdown. In the absence of special measures, in case of arcing of the insulator of the line, accompanied by a breakdown of the solid insulation of the wire, the arc of industrial frequency, which is formed with a high probability, cannot move along the wire (as in the case of non-insulated wires) and burns at the place of the insulation breakdown until the moment of disconnection of the line or until maturity under the influence of other factors. The burning time of an electric arc on PLs of medium voltage classes is quite long, because a single-phase short circuit for them is not an emergency situation and is not subject to mandatory shutdown. Quite often, re-ignition of the arc may occur at the point of breakdown. This can lead to deterioration of the insulation of the wire, damage to the insulator of the line and to the burning of the wire, which is confirmed by the experience of operating lines with protected wires. Since on a line with non-insulated

wires, the arc under the influence of electrodynamic forces is able to move one of its ends along the wire, the factor of damage to the wire due to the thermal effect of the arc was insignificant and did not affect the formation of the lightning protection concept of the PL in any way. In the case of PPL, preventing the wire from burning out becomes the main factor that determines the necessity of mandatory use of certain lightning protection measures.

Therefore, the research and development of new and improvement of known methods of lightning protection of lines with shielded wires is an urgent scientific and applied problem that must be solved by conducting scientific research and experiments.

CHAPTER 1. THE USE OF PROTECTED WIRES ON ELECTRICAL TRANSMISSION LINES AND THE INFLUENCE ON THEM OF THUNDERSTORM ACTIVITY

The advantages of overhead lines with protected wires

During the period of electrification, an extensive network of overhead power lines (OPL) was created. A significant part of these substations is actually operated beyond the normative service life, and regulatory documents focus on the use of insulated and protected wires during the construction of new substations. The use of insulated and protected wires during the construction of overhead lines will make it possible to significantly increase the reliability and cost-effectiveness of electricity supply to consumers. [1 - 7]

Foreign experience in the use of insulated wires for PLs shows that four types of wires have become widespread at this time, the design of which in European countries is based on the harmonized documents HD 626 S1 part 3 - 6 of the CENELEC committee and national standards.

A typical construction of self-supporting insulated wires with an insulated neutral carrier is that the main insulated wires and insulated auxiliary wires for street lighting circles are twisted around the insulated neutral conductor. SIP - 1A wires are distinguished by the fact that their insulation is made of light-stabilized thermoplastic polyethylene (PE), and in SIP - 2A wires, the insulation is made of cross-linked PE. The neutral conductor acts as a supporting element of the wire and serves as a neutral working (N), neutral protective (PE) or combined (PEN) conductor. Designs of SIPs with an isolated zero carrier core have become widely used in Italy, France, Belgium, Portugal, Spain, Greece, Israel, Russia, Argentina, Brazil, Malaysia, Indonesia. [4]

Insulated wires with a non-insulated carrier core are common in Finland, the Czech Republic, and South Africa. [4]

Wires insulated without a supporting element, in contrast to wires with a zero supporting core, are a bundle of insulated aluminum wires twisted into a common core. Thus, during operation, tensile forces are perceived by all veins. Designs of insulated wires without a supporting element were developed in Germany, Great Britain, Austria, Poland, Sweden and Norway. [4]

It should be noted that of all three types of insulated wires, the requirements for ensuring the reliability and safety of the power supply are met to a greater extent by SIP - 2A wires (an analogue of the Torsada wire according to NFC 33 209, France). Due to the presence of an insulated zero carrier wire, the probability of a short circuit to the zero wire is significantly reduced, resistance to the influence of corrosive environments and resistance to atmospheric overvoltages is increased, and it is also possible to perform branching without turning off the line.

The fourth type of wires is single-core shielded wires, in which the insulating layer on top of the current-conducting core acts as a protective insulation, thanks to which it is possible to reduce the distance between the wires on the PL supports and reduce the probability of a short circuit to the ground. These wires are intended for the construction of 10, 20 and 35 kV substations.

The variety of insulated wires on the market, which was formed as a result of a different approach to the selection of their types in specific power systems, leads to the need to unify wires for LPs, as is customary in the power systems of other countries, or to determine rational areas of application of insulated wires of certain brands, taking into account their parameters and operational properties. [3]

Overhead power lines with a voltage of 6 - 35 kV with shielded wires (PPL) have a number of advantages compared to power lines with non-insulated wires [5 - 9]:

- increasing safety and reducing the probability of electrocution;
- reducing the dimensions of the line;
- reduction of the width of the clearing when laying in forest areas;

- switching off short circuits between wires when they are connected, branches falling on the wires;
- increasing the reliability of lines in areas of intense ice formation.

Taking into account the mentioned advantages of the PPL, their construction in Ukraine is recommended[9 - 16]:

- in a populated area;
- with the simultaneous hanging of PPL wires with a voltage of 6 - 35 kV with overhead lines of 0.38 kV;
- in forest areas and green areas.

One of the most important requirements for the working and protective insulation of wires for PL is resistance to the influence of weather factors - solar radiation, temperature, rain, negative temperatures.

Checking the resistance of the insulation of the SIP to the influence of a complex of factors is carried out in accordance with the method recommended in HD 626 S1, part 2, by exposure to weekly cycles (168 hours).

After the effects of three test cycles are completed, the physical and mechanical characteristics of the insulation are checked. At the same time, changes in the average values of strength and relative elongation at break should not exceed 30%.

The insulation of the neutral conductor is additionally subject to the requirement of resistance to thermomechanical loads and tightness of contact with the conductive core. The tightness of the insulation adhesion to the core is checked by applying shear forces, which must be at least 180 N - for core cross-sections of 25 - 54.6 mm² and 200 N - for cross-sections of 70 - 95 mm².

The resistance to thermomechanical loads is evaluated under the influence of 500 heating cycles with the application of varying tensile forces. Tests are carried out on a special stand.

These special types of tests for SIP are mandatory when choosing materials for insulation and technological regimes of its imposition.[5]

Current regulatory documents provide for the following basic requirements for fittings for PPL:

- the tightness of the wire must be ensured during the entire service life of the line;
- fastening of a wire with a protective coating should be carried out with the help of an armature, the design of which does not damage the insulation of the wire;
- the branching of PPL wires and their connection to non-insulated lines should be carried out with the help of piercing clamps.

At the same time, the parameters of the piercing branch clamps in terms of nominal current and nominal one-second short-circuit current must be no less than the corresponding parameters of the wires they connect. The confirmation of the quality of fittings for PPL is the conduct of tests based on the European Union standard EN 50397-2 "Protected wires and fittings for overhead lines with a nominal voltage from 1 to 36 kV - Part 2: Fittings for protected wires - tests and acceptance criteria". [4]

According to the standard [5], the fittings for PPL must pass:

- mechanical tests of anchor-suspension and connecting fittings;
- testing for tightness of piercing branching and connecting clamps;
- electrical aging test;
- short-circuit current testing of devices for temporary grounding of the line;
- climatic tests.

Insulated and protected wires, taking into account their advantages and already existing experience in their operation, are now widely used in power systems, which significantly increases the reliability and economy of power supply to consumers.

However, PPLs have a significant drawback in the event of a direct lightning strike to the wire, there is a possibility of its burning, since the arc that occurs when the insulation breaks down burns in one place, not having the ability to move along the wire. [16 - 18]

Lightning surges on overhead power lines and protection against them

One of the most dangerous effects of lightning on objects of the technosphere is lightning surges. Lightning surge means an increase in voltage on the insulation or in the circuits of the object, which is caused by lightning current and can disrupt the normal functioning of the object. According to the mechanism of occurrence, lightning overvoltages can be divided into overvoltages of direct impact, associated with the spread of lightning current through the elements of the affected object, and induced overvoltages, which are caused only by the electromagnetic field of lightning and thunderclouds. During a lightning strike, voltages of the same form as the initial current pulse with amplitudes from hundreds of kilovolts to several megavolts are created in the PL, which propagate along the line at a speed close to the speed of light. [2]

The highest probability of overlap is when lightning hits the phase wires directly, therefore the primary task of the lightning protection line is to reduce the number of lightning discharges into the phase wires of the line. According to PUE [19], this is achieved by hanging lightning protection cables above them. However, as operational experience and relevant calculations show, cables do not ensure the complete absence of lightning protection, and in some cases, the efficiency of cable lightning conductors turns out to be so low that their use becomes economically unjustified. Rational lightning protection of lines is based on a set of protective measures [2, 20]. This, in addition to the suspension of cables, may include reducing the impulse resistance of the grounding of the supports, choosing the optimal line design from the point of view of technical and economic justification, the use of lightning arresters or surge arresters along the entire length of the line or at its individual points, automatic single-phase or three-phase reconnection, power supply redundancy etc. The effectiveness of each of

these measures is different, so the issue of lightning protection methods has to be decided individually for each line, taking into account its characteristics. This approach requires an engineering methodology for estimating the expected number of lightning shutdowns of the line, taking into account the measures taken to protect it. This indicator takes into account the following calculated cases of damage to the line:

- a lightning strike in the wire with subsequent overlap of the insulation between the wire and the support or between the phases;

- a lightning strike at the top of the support with subsequent reverse overlap of the insulation from the grounded support to the phase;

- a lightning strike in the middle part of the span of the cable with subsequent overlapping of the insulation from the cable to the wire or to the ground;

- a lightning strike near the power line, which is accompanied by induced overvoltages on the line that can lead to insulation breakdown.

When lightning strikes a lightning protection cable near a support, almost all of the lightning current is first directed into the ground through this support, so its consequences can be equated to the consequences of a direct strike to the support. A strike in the middle part of the cable span leads to a more uniform distribution of the lightning current between the nearby supports, which reduces overvoltages on the garlands of insulators on these supports. Induced overvoltages by themselves are capable of causing a significant number of overlaps of only overhead power lines of 35 kV and below. In calculations of the number of overlaps of lines of higher voltage classes, induced overvoltages are taken into account only as one of the factors that increase the potential difference on the insulation during direct lightning strikes to the line. Lightning surges pose a danger to both substations and substation equipment. Therefore, it is necessary to introduce effective measures to protect against them. Such measures include the use of lightning protection cables and special protective devices - non-linear surge arresters. [21]

Tasks and criteria of lightning protection of lines

The overhead line annually experiences several dozen direct lightning strikes for every 100 km of length. The main danger for the line is a direct lightning strike to the phase wires with the subsequent overlapping of the insulation from the resulting overvoltages. After the end of the lightning current pulse, there remains a conductive channel with gas that has not yet deionized at the point of overlap, through which the industrial frequency current can continue to flow under the action of the operating voltage. In the process of elimination of short circuits on the line caused by a thunderstorm, the resource of the circuit breakers is consumed; transformers and other network equipment are exposed to electrodynamic and thermal effects of short-circuit currents. A significant part of short-circuits is accompanied by the further development of accidents, which requires the disconnection of the line for a long time with a violation of the normal power supply of consumers. The analysis shows that an interruption in the electricity supply of some enterprises leads to significant financial losses [22-24]. The probability of lightning disconnection of the line depends on many reasons: the intensity of lightning activity in the areas located along the route of the line, the nominal voltage of the network, its design, the material of the supports, etc. As the voltage class of the line increases, as a rule, its length, the height of the supports, and, therefore, the probability of damage to the line by lightning. Therefore, lightning protection cables with a small angle of protection are usually hung on power transmission lines of higher voltage classes, which are carried out on metal and reinforced concrete supports, which ensures a low probability of lightning damage to the phase wires of the line, and a fairly small impulse resistance of the grounding of the supports reduces the probability of reverse overlaps from the support to the wire when lightning strikes a support or a cable near a support. The criteria for the effectiveness of lightning protection of overhead lines are the indicator of reliability of lightning protection, the curve of dangerous currents, as well as the technical and economic indicator of lightning resistance. [2]

The curve of dangerous lightning currents. The voltage on the garland of insulators depends not only on the amplitude I_l , but also on the steepness I'_l of the lightning current. The connection between dangerous combinations I_l and I'_l is described by the curve of dangerous currents. This dependence makes it possible to evaluate the influence of line characteristics (for example, grounding resistance and support inductance) on the reliability of lightning protection.

Parameters of lightning discharges

Quantitative characteristics of lightning discharges are determined by accumulating data of automatic registration of the magnitude and shape of lightning currents in objects equipped for such measurements: in line supports, lightning conductors, television masts, etc. The most accurate method of registration is automatic oscillographic recording of the curve of lightning current impulses. However, the small annual number of lightning strikes at the object of observation prevents obtaining a sufficient number of such measurements. Therefore, simplified lightning current amplitude recorders, which work on the principle of fixing residual magnetization, have become widespread. Structurally, such recorders are usually made in the form of cylinders of non-conductive ferromagnetic material about 3 cm long. They are installed on non-magnetic brackets near the body of metal supports along the lines of force of the magnetic field of the current passing through the support during a direct lightning strike. Before installation, the loggers are calibrated by placing them in a solenoid with a known magnetic field strength and then measuring their residual magnetization using a ballistic galvanometer. Then the rods are demagnetized in a gradually decreasing alternating magnetic field [25].

The accuracy of measuring the amplitude of a single lightning current pulse with such recorders is relatively small: the error can reach 15-25%, but this shortcoming is compensated by the possibility of mass measurements with the simultaneous installation of recorders on a large number of supports, which, while reducing the

systematic error, allows you to significantly increase the accuracy of statistical estimates of the distribution of values lightning current.

With multiple repeated lightning discharges, the simplest recorders are able to record only the amplitude of the largest lightning current pulse. In cases where it is necessary to take into account the characteristics of the first and second discharges separately, it is necessary to use only the results of the oscillographic recording of the lightning current curve. Data on the statistical relationship between the amplitude and steepness of lightning currents can also be obtained practically only with the help of oscilloscopes [26].

Along with the mentioned methods, lightning discharge characteristics are also studied with the help of oscillographic recording of current pulses in lightning conductors and voltage pulses on antennas located above the earth's surface, in case of nearby lightning discharges.

A typical shape of a current pulse in an object struck by lightning is shown in fig. 1.5. From the point of view of lightning protection, the main parameter of the lightning current impulse $I_l = I_l(t)$ is the amplitude of the lightning current I_l , which for brevity will be called simply the lightning current. Another parameter that determines, along with the lightning current, the magnitude of overvoltages in the affected object is the steepness of the lightning current, i.e. the speed of growth on the pulse front $I'_l = dI_l/dt$. Since the instantaneous values of the rate of current growth at different points of the front are different, usually the steepness of the lightning current is understood as its average value: $I'_l = I_l/\tau_f$. The duration of the pulse front τ_f is usually determined in the following way. The front points corresponding to current values of $0.3I_l$ and $0.9I_l$ are noted on the current pulse graph. A straight line is drawn through these points to the intersection with the zero current level (abscissa axis) and with the current amplitude level (see Fig. 1.1). Projections of these intersection points on the abscissa axis are conventionally taken as the moments of the beginning of the pulse and onset of the pulse amplitude, and the time interval between them is the duration of the front.

After reaching the amplitude, the lightning current pulse decreases relatively slowly to the zero level. The wavelength, or the duration of the lightning current pulse, is usually estimated by the half-life time τ_f (see Fig. 1.1), that is, the time interval from the conditional beginning of the pulse to the moment when the pulse curve, which has passed through the maximum, decreases to a current value equal to half the amplitude [26].

The amplitude and steepness of the lightning current can have different values. The averaged curves of the statistical distribution of I_l and I'_l for individual lightning discharges are shown in fig. 1.2 and 1.3. It should be noted that the method of determining I'_l values and the corresponding accuracy in different studies differed significantly, therefore the few data on the distribution of the steepness of lightning currents, as well as the data below on the distribution of front durations $\tau_f = I_l/I'_l$, are of an approximate nature.

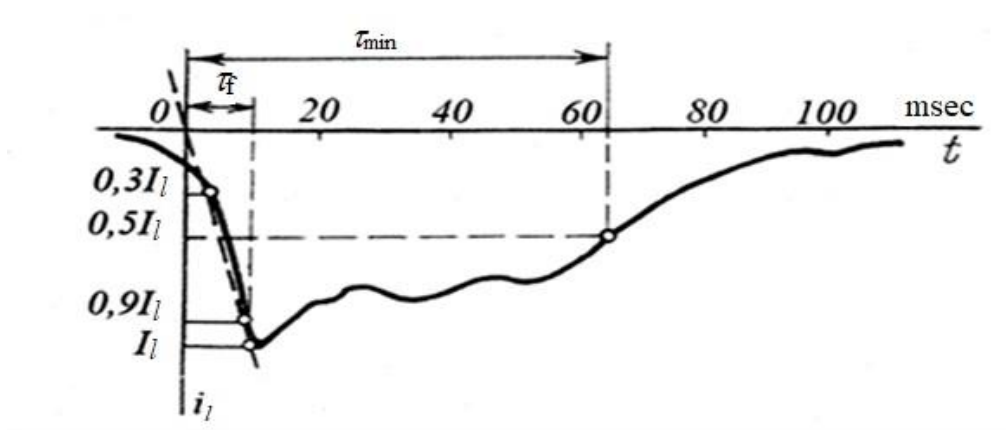


Figure 1.1 - Lightning current oscillogram

It is customary to provide statistical data on the parameters of lightning currents using distribution graphs with a probability scale (normal-logarithmic scale), on which the probability distribution is a straight line. Mathematically, the probability that the parameter we are interested in (pulse amplitude, steepness, etc.) is equal to or will exceed a given value is found by the formula [27]:

$$P(x) = \frac{1}{\sqrt{2\pi} \cdot x\sigma} \exp \left[-\frac{1}{2} \cdot \frac{\ln^2 \frac{x}{x_{50\%}}}{\sigma^2} \right], \quad (1.1)$$

where is $x_{50\%}$ - the average or 50% value of the parameter;

σ – the relative deviation, which is defined as the logarithm of the parameter ratio at probabilities of 16 and 50%:

$$\sigma = \ln(x_{16\%} / x_{50\%}). \quad (1.2)$$

So, in order to give an idea of the characteristics of the distribution of the maximum values of lightning currents, which were obtained by various authors, in the table. 1.1 provides information on currents $I_{50\%}$ with $P=50\%$ and $I_{16\%}$ with $P=16\%$:

Table 1.1 - Values of currents $I_{50\%}$ and $I_{16\%}$ according to the data of various authors

Author	$I_{50\%}$, kA	$I_{16\%}$, kA	Note
Brown, Twander	13	27	–
Chianos, Pierce	20	50	–
Popolansky	25	61	–
Spurs	25	66	–
Berger	28	60	Only the pulses of the first main discharges
Hunchbacks and others	26,5	54	The same
Anderson, Erickson	31	62	All grades
Ikeda	20	41	During the summer season
	30	68	
	36	61	
The international project	31	70	–

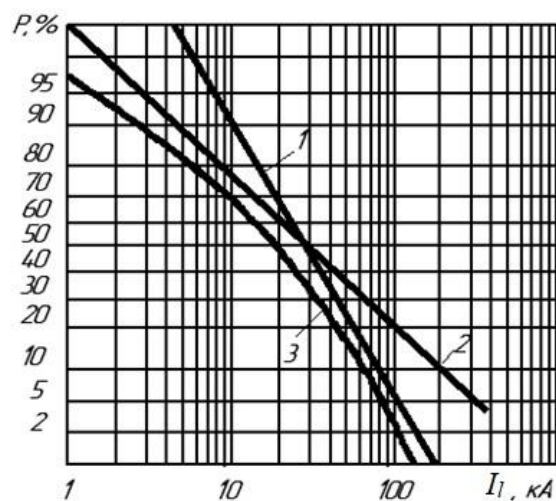


Figure 2.1 – Statistical data on the maximum values of lightning currents: 1 – measurements by K. Berger; 2 – measurement by E. Garbanyati; 3 – calculation according to (1.3)

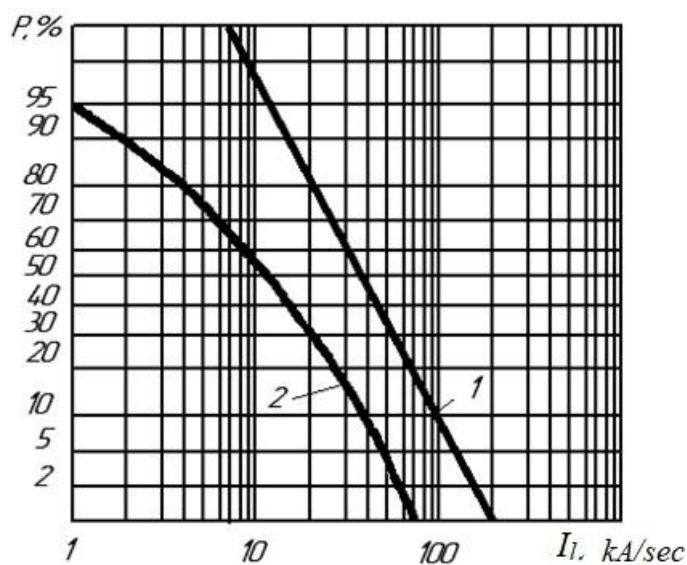


Figure 3.1 – Statistical data on the steepness of lightning currents: 1 – repeated pulses of negatively charged lightning; 2 – calculation according to (1)

Also interesting are the data of extensive measurements [27, 28] of lightning characteristics (more than 2 million strikes), which were carried out in France in 1987-1989. The measurements were carried out using a system of 16 observation stations covering the entire territory of France and a data processing center.

Evidence was obtained about the distribution of the density of lightning strikes to the ground, about the polarity and amplitude of lightning currents (the first components of the strikes). It is interesting that very large values of lightning currents were recorded in a significant number of lightning strikes (Table 1.2). Lightning strikes with a current of more than 200 kA accounted for 0.71%, of which 75% had positive polarity.

Shocks with currents of more than 200 kA occurred throughout the year and throughout the country. Currents with extremely large amplitude (up to 950 kA) attract attention. With a negative polarity of 50%, the value of the current is 34.3 kA, with a positive polarity – 80.9 kA.

Table 1.2 - Number of lightning strikes with an amplitude of more than 200 kA (France 1987-1989)

Polarity lightning current	The number of lightning strikes with current is greater			
	200 kA	400 kA	600 kA	800 kA
Negative	3442	112	17	1
Positive	9093	409	42	5

Remote methods for determining the parameters of lightning currents, which were used in these measurements, are characterized by high performance, but do not allow obtaining data that would fully correspond to a real strike. This is due to the fact that any, even complex channel model will always differ from the real channel. In particular, the role of channel branches in the formation of pulses of electric and magnetic fields, which are registered at observation points, remains unclear.

In the approximate calculations, the averaged distributions of I_l and I'_l are used without taking into account their difference at the first and next pulses. In this case, statistical distributions can be approximated by exponential functions of the form [29]:

$$P(I_l) = \exp(-0,03I_l); \quad P(I'_l) = \exp(-0,06I'_l), \quad (1.3)$$

where $P(I_l)$ and $P(I'_l)$ are the probabilities that the amplitude (or steepness) of one lightning strike will exceed the specified value

There is a weak positive correlation between the amplitude and steepness of the lightning current, that is, larger current amplitudes generally correspond to larger steepness values, and vice versa. However, the data available at this time are not sufficient to obtain a reliable quantitative assessment of this relationship. As a first approximation, the two-dimensional distribution function of I_l and I'_l , taking into account their relationship, can be represented as:

$$P(I_l, I'_l) = \exp(-\alpha I_l - \beta I'_l + \gamma \sqrt{I_l I'_l}), \quad (1.4)$$

where α , β and γ are empirically selected parameters [29].

Because of the relatively weak statistical connection between I_l and I'_l , in calculations, the amplitude and steepness of the lightning current are often taken as statistically independent random variables. With:

$$P(I_l, I'_l) = \exp(-0,03I_l - 0,06I'_l) \quad (1.5)$$

The length of the front τ_f and the wavelength τ_w of a thunderstorm discharge are random variables, and their statistical distributions also differ significantly during the first and second discharges. The first discharges are characterized by relatively longer front lengths and longer wavelengths compared to repeated discharges. Approximate distribution curves of values τ_f and τ_w are shown in Fig. 1.4 and 5 [30]. As can be seen, the length of the front for the first lightning discharge ranges from 2 to 10 μs with an average value of 5 μs . For repeated discharges, it is significantly less - on average 1 μs .

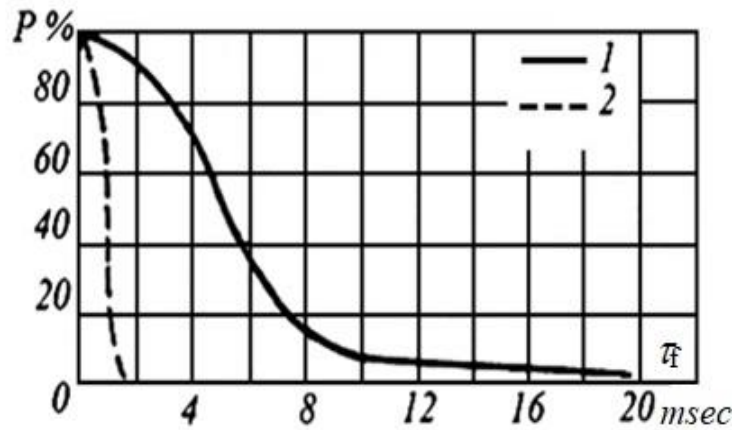


Figure 1.4 – Statistical distribution of durations of the front of lightning current pulses during the first (1) and repeated (2) discharges

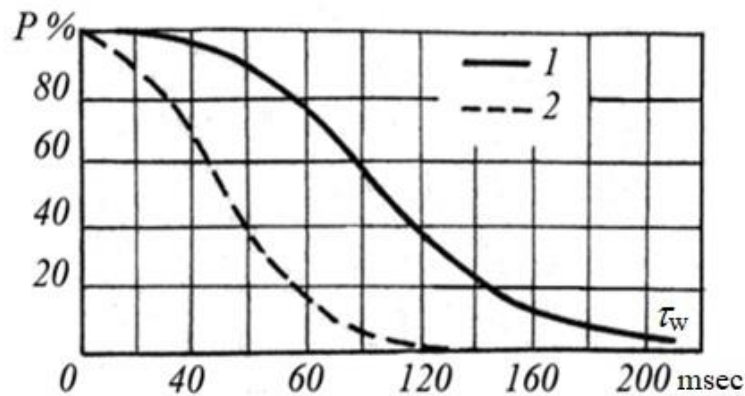


Figure 1.5 – Statistical distribution of the half-life duration of lightning current pulses during the first (1) and repeated (2) discharges

The wavelength of the first digit is 20...200 μs with an average value of 100 μs . In repeated discharges, it is approximately half as much: an average of 50 μs . The time intervals between repeated discharges vary from 0.01 to 0.5 s, on average they are 0.06 s. Single lightning is observed in 50% of cases, in other strikes the number of lightning discharges ranges from 2 to 10. In some cases, lightning with the number of discharges over 20 was noted.

The total duration of lightning is usually 0.1 - 1 s.

The distribution curve of time intervals between repeated discharges is presented in Fig. 1.6, and the histogram of the distribution of the number of lightning discharges during one lightning strike is in Fig. 1.7.

For calculations of overvoltages in objects affected by lightning, it is necessary to adopt an equivalent scheme of replacing the lightning channel with the current flowing into the object.

Usually, the section of the lightning channel, which is located at a height of several hundred meters above the earth's surface and plays the main role in the formation of the amplitude of the lightning current in the object, is used in calculations to be replaced by a homogeneous single-conductor line without losses with a wave resistance z_l , along which a wave with a voltage amplitude $0.5I_l z_l$, or a current source I_l with its own conductivity $Y_l = 1/z_l$.

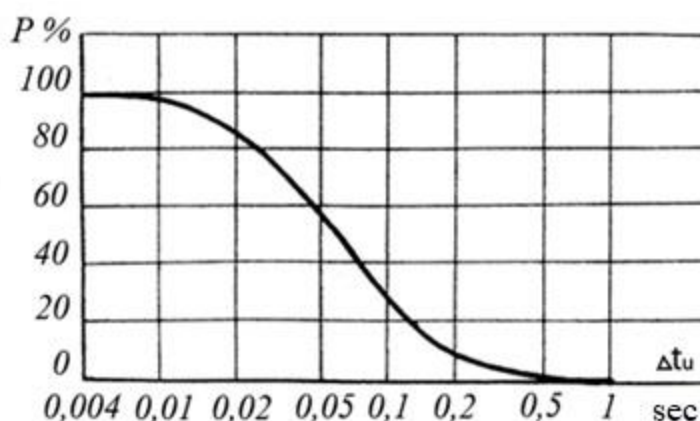


Figure 1.6 – Curve of distribution of time intervals between repeated lightning discharges

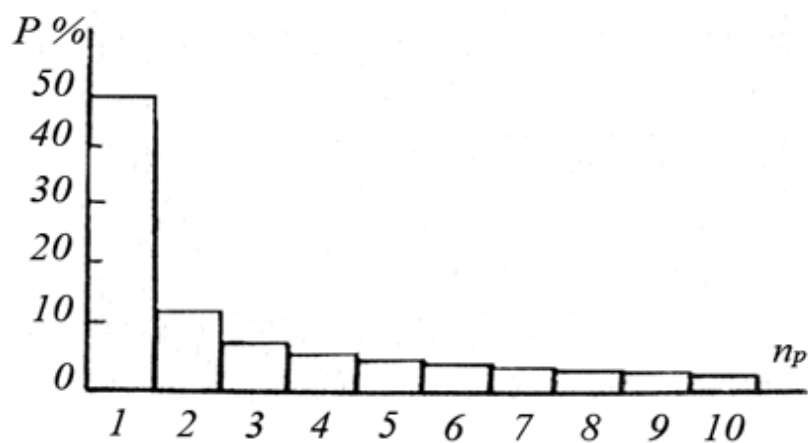


Figure 1.7 – Histogram of the distribution of the number of lightning discharges during one strike

The wave resistance of the lightning channel z_l is a conditional value, since the channel of the main stage is formed during the growth of the lightning current and changes its characteristics depending on the time and current of the lightning, as well as on the height of the considered section of the channel.

The speed of movement of the top of the main stage of the discharge from the affected object to the cloud is not equal to the speed of light, but is 7-50% of this value, and near the ground it is approximately 1.5 times higher than the average along the entire length. Indirect experimental data and theoretical studies show that $z_l = 140 (1 + 240 / I_l)$ it varies from 1-10 k Ohm (at low currents) to 300-600 Ohm (at extremely large lightning current amplitudes). Since lightning strikes with larger current amplitudes are the greatest danger, it is recommended to take the smallest of the specified values in the calculations of lightning protection of power transmission lines: $z_l = 300 \text{ Ohm}$.

Occurrence of lightning discharge

Electric discharge between charged areas of a thunderstorm cloud and the ground can occur in the form of linear, ball lightning, and silent discharge (Fig. 1.7).

Linear lightning in its main features is similar to an electric discharge between the electrodes of a voltage pulse generator (some of its differences from a laboratory discharge will be discussed below). Linear lightning is observed most often and is the main source of atmospheric overvoltages.

Ball lightning still has no analogues among the types of discharge obtained in the laboratory, and is not sufficiently studied at this time. It appears in the form of a brightly luminous moving body, capable of moving in the atmosphere and penetrating through solid partitions (windows, etc.).

According to one of the existing theories, ball lightning occurs at the bend of linear lightning (Fig. 8). Electrodynamic forces acting in the place of a sharp bend tear off part of the plasma. Having existed "autonomously" for some time, ball lightning disintegrates, and sometimes its disappearance is accompanied by a strong explosion. When striking a power line, ball lightning does not create large overvoltages, so it is not considered in the course "Overvoltages in high-voltage electrical networks and protection against them".

A silent discharge (St. Elmo's lights) occurs on sharp, rising objects during a thunderstorm with high electric field strength above the earth's surface.

This type of discharge is also not a source of significant atmospheric overvoltages.

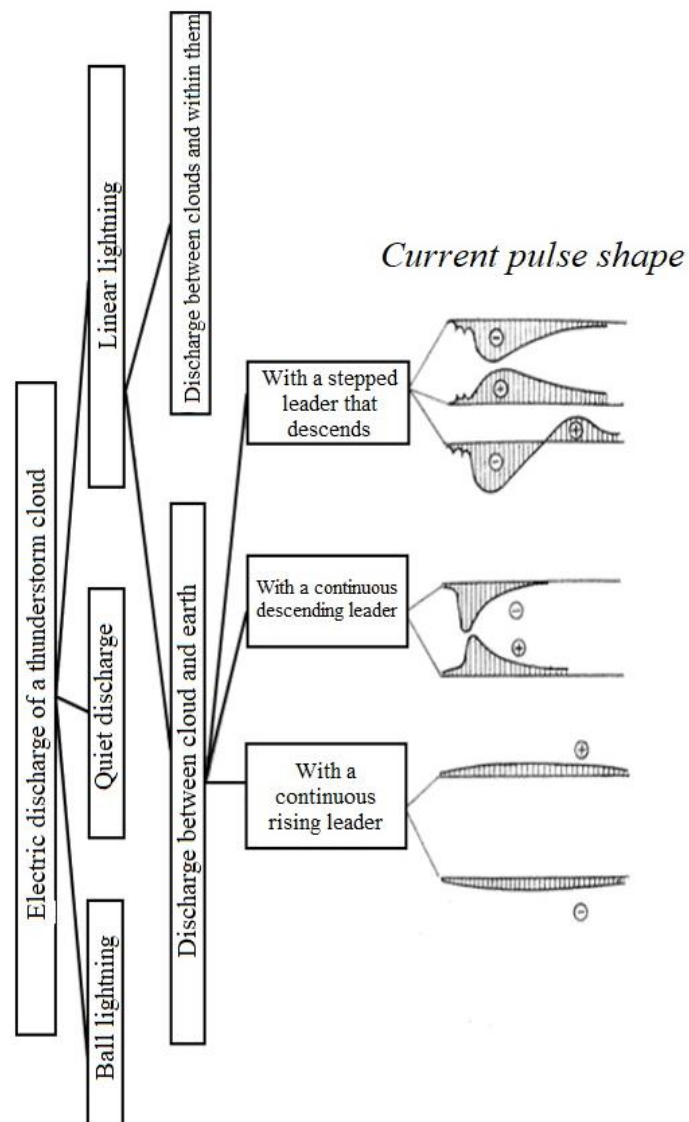


Figure 1.8 – Classification of lightning discharges

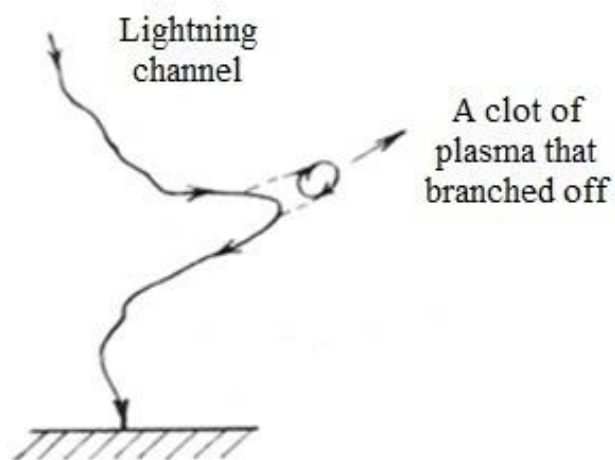


Figure 1.9 – Scheme of formation of ball lightning

In 1752, B. Franklin in America, and in 1753, M. Lomonosov and G. Richman in Russia experimentally proved the electrical nature of lightning for the first time. Further research confirmed Franklin and Lomonosov's hypothesis that linear lightning is an electrical breakdown of a giant gap between the cloud and the ground.

In the 1930s, new devices began to be used to study lightning: cathode oscilloscopes, Boyce cameras (cameras with rapid mutual movement of film and photo images), and later - electronic-optical converters. Research by I. S. Stekolnikov, V. A. Lamdon, V. S. Komelkov, E. M. Bazelyan (USSR), Schonland (African countries), McIron (USA), Berger (Switzerland), Spohr (PNR) and other scientists allowed to determine the most important statistical characteristics of lightning, necessary for the development of the basic principles of lightning protection. At this time, these studies are ongoing.

The main prerequisite for the development of linear lightning is the formation of a sufficiently high density of excess charges of positive or negative polarity in a limited volume of the thunderstorm cloud cell and the associated increase in the average electric field strength to 100–500 kV/m [31]. In individual points of this area, the local tension can reach 1–3 MV/m due to local inhomogeneities of volume charges. At the same time, there are conditions for the development of electron avalanches, which lead to the further development of ionization processes and the formation of streamer channels. The currents of individual streamers, merging, heat up individual channels to a temperature of 10⁴ K, at which the conductivity of the channel increases sharply due to thermal ionization of the gas, and a leader channel is formed. The leader formed in the negatively charged part of the thunderstorm cloud is similar in structure to the leader of a long laboratory spark and consists of a channel, a head, and a streamer zone. Through the conductive channel of the leader, which has a linear resistance of ~50 Ohm/m and a longitudinal electric field strength of ~10 kV/m, the potential of the cloud is transferred to the head of the leader, around which a zone of streamer discharges develops (Fig. 1.10). The streamers carry the negative charge from the leader channel and create a volume

charge around the formed leader channel. In the radial direction, the volume charge density is set in such a way that the electric field strength from the channel to the boundary of the streamer zone is approximately the same, equal to the critical value $E_{kr} = 200...500$ kV/m, i.e. the field in the middle of the volume of the streamer zone is equigradient. From this condition, it is possible to determine the law of decreasing charge density in the volume surrounding the channel of the leader: in the radial direction, the charge density decreases according to a linear law to the boundary of the streamer zone

$$p(r) = \frac{\varepsilon_0 E_{kr}}{r} r_{lead} \leq r \leq r_{str} \quad (1.6)$$

where r_{lead} is the radius of the leader channel;

r_{str} – the radius of the outer border of the streamer zone

Measurements of lightning discharge parameters show that the value of the total charge per unit length of the leader q_{lead} is 10^{-3} Kl/m. This makes it possible to estimate the order of magnitude of the radius of the outer border of the streamer zone of the leader (ignoring the influence of external electric fields) from the ratio

$$r_{str} = q_{lead} / \varepsilon_0 E_{kr} \cdot 2\pi \approx 100 \text{ m}$$

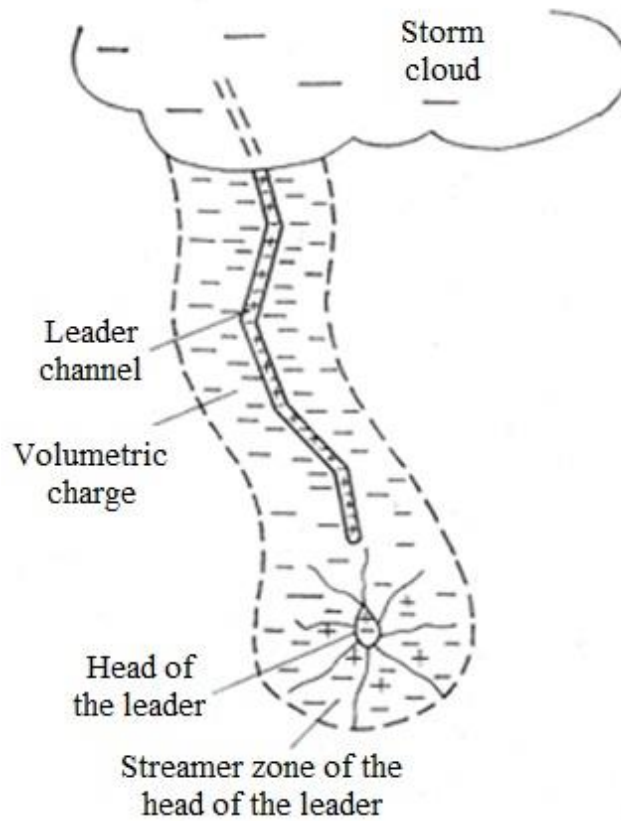


Figure 1.10 – Lightning leader development scheme

The potential of the channel in this case is $U_{lc} = r_{str} E_{kr} \approx 50 \cdot 10^6$ V, which coincides with the experimental data.

Thus, the growth of the leader's channel is accompanied by the formation around it of a volume charge zone of the same polarity as the charge of the thunderstorm cloud cell. The charge density decreases - in the first approximation, inversely proportional to the distance from the axis of the channel.

The direction of advancement of the leader's head depends on the local inhomogeneities of the field and the structure of the air masses and is therefore not stable. Available experimental data show that in mid-latitudes only 30-40% of thunderstorm discharges reach the earth's surface, the rest occur between clouds or between different parts of the same cloud. In equatorial zones, the share of lightning discharges to the ground is only 10-20%. If the advance of the leader to the ground takes place along a path not prepared by previous lightning discharges, breaks in

the movement of the leader are observed after passing segments 10-100 m long. These pauses last 30-100 μs . They can be detected in photographs of lightning taken by special cameras (Boyce cameras), where at the time of shooting, the photographic film quickly moves relative to the image of the leader in a direction perpendicular to the path of its movement. A simplified view of such a photo (boysgram) is shown in fig. 10 [31]. The rate of elongation of such a stepped leader during its growth periods is of the order of $(3 - 10) \cdot 10^5 \text{ m/s}$. With repeated lightning discharges, which develop after a time not exceeding hundreds of milliseconds after the first discharge, the leader, as a rule, develops continuously and is called an arrow-shaped leader. With an increase in the duration of the pause between the discharges, the air gap has time to partially restore its insulating properties, and large steps begin to appear again in the leader's advance.

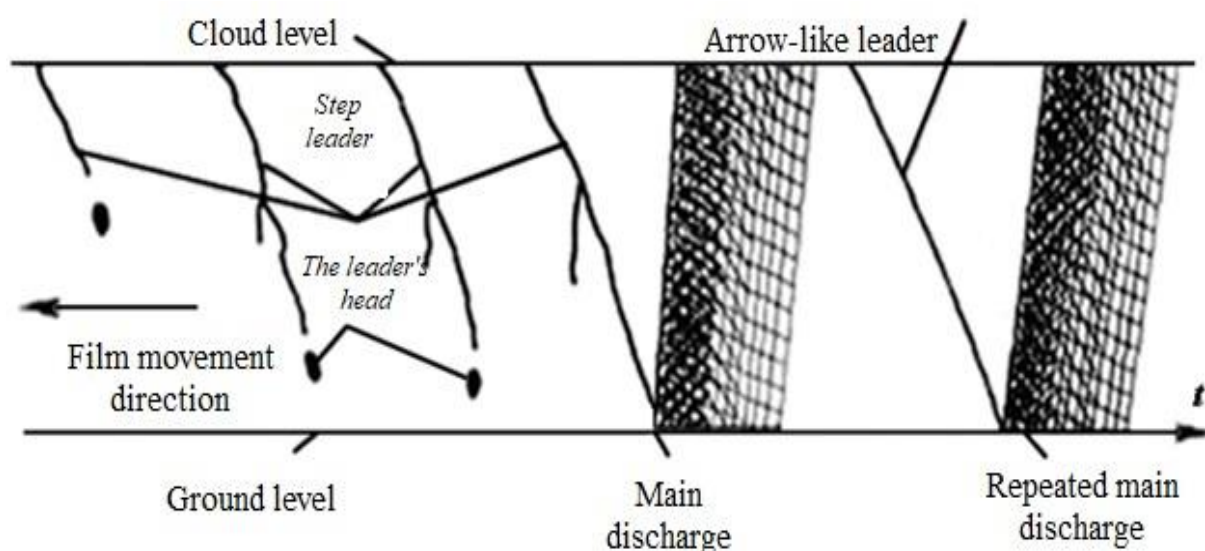


Figure 1.11 – Boyzogram of linear lightning

The stepwise nature of the development of the leader in air is also observed in laboratory conditions for long gaps with a slow rise of the applied voltage (at a rate of less than $5 \text{ kV}/\mu\text{s}$), as well as with limited source power.

The radius of the streamer zone around the leader's head is estimated to be several tens of meters. Objects located outside this zone have a weak influence on the formation of the path of the leader's development, therefore, at a height $>150 \text{ m}$ above

the surface of the earth, the direction of advancement of the leader does not depend on the location of ground objects. However, starting from the moment when the streamer zone of the leader reaches the upper parts of such objects, the leader's path is oriented towards them. Counter leaders developing from high ground objects towards the lightning leader can also contribute to this. The length of the channel of the opposite leader at an object height of 20 m is 20 - 30 m, and at a height of 200 m it increases to 50 - 100 m.

The connection of the channels of descending and counter leaders or the sprouting of the channel of the descending leader to the earth's surface is the completion of the initial stage of lightning development - the creation of a continuous conductive channel from the charged part of the cloud to the ground [31].

Before collision with ground objects, the potential of the channel is close to the potential of the cloud. During contact, the potential of the lower end of the leader decreases by 2-3 orders of magnitude. This disturbance propagates from the ground up the channel at a speed close to the speed of light. A decrease in the potential in the channel leads to a sharp increase in the radial intensity of the electric field between the volume charges and the channel of the leader, as well as to the formation of "reverse discharge" streamers, thanks to which the volume charge begins to flow down the channel into the ground. This current heats the channel up to $(2...3) \cdot 10^4$ K, its linear resistance decreases by 2 orders of magnitude - less than 1 Ohm/m, which leads to a further increase in current to tens and sometimes hundreds of kiloamperes. This stage is called the main stage of the lightning discharge. The process of transforming the leader channel into the master stage channel propagates from the ground to the cloud at a speed of tenths of the speed of light. The bright glow of the channel of the main stage is perceived by the eye as a flash of lightning, and the rapid expansion of the gas when heated by the current of the main stage and its subsequent cooling and compression generate an acoustic wave - the thunder of lightning [32].

The current pulse of the main stage usually lasts several tens of microseconds until the intensity of the process of neutralization of volume charges around the channel

weakens. The frontal part of the pulse is completely determined by the volume charge neutralization current around the leader channel, and the decay of the pulse is also determined by the redistribution of charges in the middle of the thunderstorm cloud. The final stage follows the main stage, which is accompanied by the flow of a relatively small current (of the order of tens of amperes) through the cooling channel for several tens of milliseconds.

After the first pulse of lightning current, intracloud discharges can restore the conditions for the development of the leader channel, and a second discharge develops.

The considered process of development of linear lightning by the growth of a leader from a negatively charged part of the cloud to the ground is typical for lightning strikes in low (up to 30 m) ground objects on flat terrain. In this case, 80...90% of lightning strikes transfer a negative charge to the ground. Discharges from positively charged parts of the cloud with a positive trailing leader are also occasionally observed. Such discharges are distinguished by the long duration of the lightning current pulse, larger current amplitudes, and the absence of repeated discharges.

When lightning strikes high (>100 m) objects, as well as in mountainous terrain, discharges are observed, in which the development of the leader begins from the object that is struck, upwards, in the direction of the thundercloud (lightning with an ascending leader). In a flat area, the share of such lightning at an object height of 100 m is 7%, at a height of 200 m it increases to 25%, and at a height of 380 m it reaches 96%. In a mountainous area, the number of lightning strikes with an ascending leader, striking even low objects, is about 75% of the total number of lightning strikes to these objects. Discharges with ascending leaders have a longer duration of the currents of the main stage (up to 0.1 s) and a relatively small amplitude of current pulses (of the order of several kiloamperes). With the development of repeated discharges, the arrow-shaped leader begins to develop from the cloud to the ground, just as in lightning with a descending leader of the first discharge.

Features of lightning protection PL 6 - 35 kV

The suspension of lightning protection cables, which is the main lightning protection measure on lines of voltage classes 110 kV and above, is not very effective for lines 6 - 35 kV, which is caused by the low impulse strength of the 6-35 kV insulation. As a result, the probability of reverse overlaps during lightning strikes in the support or in the cable would be quite significant, with normal values of the grounding resistance of the supports. Therefore, 6-35 kV lines are built, as a rule, without cables. Exceptions are only particularly responsible 35 kV lines on metal supports.

Despite the absence of cables, 6-35 kV lines have a number of features that create more favorable conditions for their lightning protection. [33, 34]

Firstly, these lines are less likely to be directly struck by lightning due to their relatively small height and length. Often they are partially protected from direct lightning strikes by objects located near the rising line: buildings, tall trees, lines of higher voltage, etc.

Secondly, the presence of an isolated or grounded neutral through an arc extinguishing reactor in networks of 6 - 35 kV facilitates the fight against the consequences of impulse overlaps of insulation, contributes to extinguishing the arc of a single-phase earth fault. It can be assumed that cases of lightning overlaps of the insulation of only one of the phases of the line do not cause its disconnection. The resulting arc of a single-phase overlap extinguishes, and the danger for 6 - 35 kV lines is represented only by overlaps between phases or simultaneous overlaps from several phases to the ground. With interphase overlaps, the probability of arc extinction remains high, because the operating voltage gradient along the overlap path on these lines is small.

Thirdly, 6 - 35 kV lines are often built on wooden supports. In this case, the length of the path of the lightning overlap of the insulation increases due to the impulse strength of the tree of the traverse and the support rack. The probability of overlap and the probability of transition of pulse overlap into a short-circuit arc decreases.

However, these advantages of wooden supports cannot be fully realized due to the possibility of splitting wooden parts during direct lightning strikes. In order to combat the splitting of the traverses and struts of the supports, in some cases it is necessary to shunt the wooden parts of the supports with current-carrying metal descents.

Unlike lines of a higher voltage class, lines of 6 - 35 kV on metal supports are often disconnected due to the effect of induced overvoltages, which can cause the overlap of the 35 kV insulation, five times more than the number of overvoltages dangerous for the 110 kV network. The reason for this is also the low impulse strength of the insulation of 6 - 35 kV lines on metal supports.

35 kV lines on metal supports are protected by cables only in particularly critical cases. Usually they are lightning-proof even without cables. As mentioned above, the main lightning protection measures here are the use of an insulated neutral or an arc-quenching reactor, as well as an ASR. For these lines, a certain proportion of disconnections is determined by induced overvoltages.

35 kV lines on wooden supports have a higher reliability of lightning protection due to the use of high impulse strength of wood.

Estimates of their specific number of disconnections are indicative, since the impulse strength of wood, according to literature, can vary two to three times depending on the degree of moisture and the condition of the wood. In addition, the grounding resistance of reinforced concrete steps on wooden supports that do not have current-carrying descents is not normalized, which can lead to a large spread of its values on the real line.

Lines 6 - 20 kV on both metal and wooden supports also do not have cable protection and are protected from lightning effects with the help of an arc extinguishing reactor or an isolated neutral and ASR. Spark gaps or valve arresters are installed on supports with weakened insulation or with an increased probability of lightning damage [35].

Above, when calculating the expected annual number of lightning shutdowns of PL 6 - 35 kV, it was assumed that the insulation along the line is uniform and there are no separate places with weakened insulation. However, there are always places on real lines that, in the absence of appropriate protection measures, can lead to a significant increase in the expected annual number of lightning shutdowns.

In recent years, non-linear overvoltage limiters are increasingly being installed on 6-35 kV lines to protect weak points.

Individual places of lines require additional protection measures. Such places include [36, 37]:

- intersection of power transmission lines with each other;
- intersection of power transmission lines with communication lines, tram tracks and electrified railway lines;
- supports of power transmission lines with reduced electrical insulation strength;
- high supports of transitional spans;
- branches to substations for unsoldering and sectioning disconnectors on lines.

The protection of crossings of power transmission lines is caused by the need to prevent serious accidents in the event of a thunderstorm overlap from the upper line to the lower power transmission line or communication line. Such overlaps can cause false operation of relay protection and system accidents, damage to electrical equipment of lower voltage lines and even cause human casualties. The greatest danger is a lightning strike in the crossing span. The distance between the wires of intersecting lines in this span should be quite large, and the amplitude of overvoltages is limited by arresters or surge arresters located as close as possible to the intersection. Therefore, in the crossing span, it is advisable to remove the lightning protection cable from the lower line and choose the crossing point further from the middle of the upper line span.

If the distance from the intersection to the nearest support does not exceed 40 m, arresters or surge arresters can be installed only on the nearest support. On lines up to

35 kV that have an anti-retarder device, protective gaps can be installed instead of arresters. the resistance of the grounding of the resistances of the span of the intersection should not be higher than 10 ... 20 Ohms. If the supports are wooden, then it is recommended to install tubular arresters or surge arresters on them parallel to the garlands, or spark gaps connected by descents to the grounding devices of the support.

The required vertical distance S between the wires of intersecting lines depends on the nominal voltage of the upper line, the grounding resistance of the supports, the length of the span and the distance between the intersection and the nearest support (Table 1.3). As can be seen from the table, the installation of protective equipment allows to reduce the distance S by 20 - 30%.

Table 1.3 - Minimum permissible distances between wires of overhead lines

Voltage of the upper line, kV	The length of the span of the intersecting line, m	The smallest permissible distances S between the wires of cross lines, m			
		at the shortest distance from the point of intersection to the nearest support of the upper line with the arrester, m			in the absence of special lightning protection measures of the intersection
		30 – 70	70 – 100	100 – 150	
35	To 200	3	3 – 4	-	5
	200 – 300	3 – 4	4 – 5	4 – 5	
6 – 20	To 100	2	-	-	4
	100 – 150	2 – 2,5	-	-	

Separate metal and reinforced concrete supports of the lines, made mainly on wooden supports without cables, represent a place with reduced impulse electrical strength of the insulation. It is advisable to protect these places with three-phase sets of valve arresters or non-linear overvoltage limiters.

High transitional spans of PL are sources of increased number of thunderstorm shutdowns. This is due to the high height of supports and wires above the ground (water), which leads to an increase in the number of lightning strikes in the span, a

decrease in the effectiveness of cable protection, and an increase in the number of reverse overlaps due to the large inductance of the supports. reducing the impulse resistance of the grounding of the supports in this case becomes insufficient. [37, 38]

The calculation of the expected number of shutdowns of submarines with high transition spans is complicated by the need to take into account the complex topography of the terrain under the span and the large difference in the height of the wire above the ground in certain sections of the span. Therefore, lightning protection of responsible spans is considered individually. As the calculations show, the most effective means of protecting high transitions is the installation of LSA or OVL in the upper part of the transition supports or on supports adjacent to the transition supports.

CHAPTER 2. METHODS OF EXPERIMENTAL RESEARCH

Investigation of the probability of PL damage on a large-scale model using long pulses

The existing norms and recommendations [16], which determine the protection zones of lightning conductors of a relatively small height, are based on laboratory studies [20, 26 - 30] performed in the 30s and 40s on small-sized models when using a voltage pulse with a steep front, and also on rather limited field observations of lightning damage to various objects, including those protected by lightning rods [29 - 31].

When researching the protective action of lightning conductors on models, one of the main issues is the compliance of the conditions for the development of a discharge in the gap between the cloud and the ground (lightning) and in the laboratory gap. Lightning is characterized by a zigzag channel, due to its gradual development and the random direction of development of each stage at a low average discharge voltage - about 15 kV / m. To reproduce the random nature of the direction of discharge development in laboratory studies, it is necessary to obtain the lowest possible average discharge voltage, which provides a stepwise the development of the spark channel with a sufficiently large ratio of the length of the discharge gap to the length of the leader step and, accordingly, the random direction of the path of the discharge development. From this point of view, the use of a voltage pulse of positive polarity with a gentle front (several thousand microseconds) is justified, in which the average discharge voltage in a sharply inhomogeneous field (rod-plane type) rapidly decreases with an increase in the length of the gap and for a distance of 15 m is about 150 kV / m. With negative polarity, the average discharge voltage for the rod-plane gap is much larger. There is no data on the electrical strength of gaps up to 15m with negative polarity in the literature. For shorter spans ($S = 2 \div 3$ m), the discharge voltage at negative voltage polarity (~ 1000 kVA / m) more than doubles the discharge voltage at positive polarity (~ 400 kV / m).

The use of gentle voltage pulses in laboratory studies of lightning protection can be justified by the following considerations.

When the lightning channel moves from the cloud to the ground, the field strength near the protected object increases relatively more slowly. The build-up time of the field strength can be estimated based on the average length of the lightning channel (1000-2000 m) and the average speed of its development $((1-2) \cdot 10^5 \text{ m/sec})$ - about 0.005-0.02 sec) [39].

The same result is obtained when estimating the voltage build-up time over the entire gap between the cloud and the ground. An estimate of this time can be given based on the interval between subsequent lightning discharges through the same channel (0.3-0.0002 sec) [39]. Intervals of such a long duration cannot be explained by the development of a channel from the nearby charged center of the cloud, since the dimensions of the cloud are unrealistically large. Therefore, the intervals between repeated discharges give an idea of the rate of accumulation of charges and, accordingly, the growth of the potential of the thunderstorm center of the cloud.

A similar conclusion can be reached when analyzing the nature of the voltage change during the development of lightning and discharge in the laboratory interval. In real conditions, the duration of voltage application does not limit the time of lightning development, and therefore it occurs at the minimum possible average field strength in the discharge interval. When researching on models, the duration of the voltage effect should ensure the development of the leader within the front of the applied pulse, and not far behind the maximum, as it happens with a standard pulse shape. Since the development time of the leader in the interval of 10-15 m can be about 100 μsec at the minimum average discharge voltage [39], the length of the front should be at least an order of magnitude greater, that is, at least 1000 μsec . On the other hand, an excessive increase in the length of the pulse front can lead to difficulty in the development of the leader caused by the movement of the volume charge of ions $K_u = 2 \text{ cm}^2/\text{V}\cdot\text{s}$ and a field strength of about 20 kV / cm, the speed of ion movement is $V_u = 4 \cdot 10^4 \text{ cm / Sec}$. To

prevent the movement of the volume charge to a distance of more than 10% of the length of the gap for the front (t_f) no more

$$\frac{100-150}{4 \cdot 10^4} = 2500 - 3750 \text{ нс}$$

The method of research using long pulses is well used on large-scale models with a breakthrough distance of more than 3 meters, when it is possible to simulate lightning with a leading discharge shape, for this, equipment of sufficiently high power is required.

Study of PL vulnerability taking into account the height of lightning orientation

Determining the height of lightning orientation

Studies have shown [39] that the process of orientation does not begin from the moment of the appearance of a descending leader, but only after its channel moves some distance into the depth of the gap, and the head of the channel reaches a level called the height of orientation (H_0). Therefore, the distance to the high-voltage electrode should not be entered into the calculation of the probability of orientation, but the distance from the grounded electrode and the plane to the head of the channel of the descending leader at the level of the orientation height (Fig. 2.1).

Up to the orientation height, the downward leader develops, practically not reacting to the presence of grounded electrodes. The deviations of its trajectory are random and equally probable in all azimuthal directions, so that the averaged trajectory for many discharges coincides with the vertical axis of the gap (Fig. 2.1).

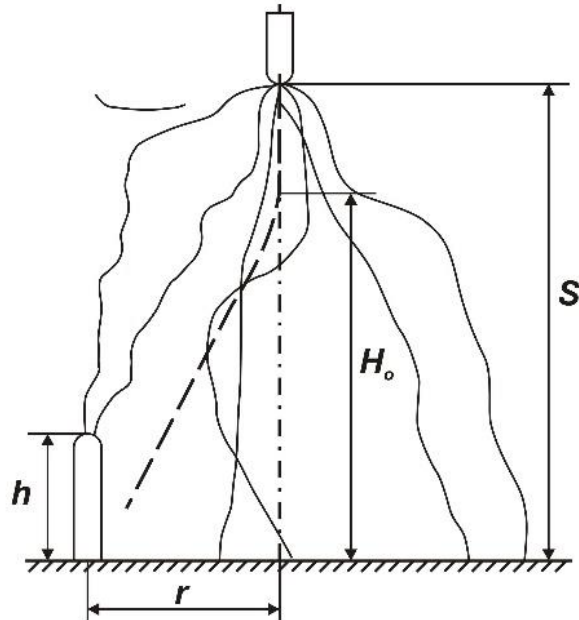


Figure 2.1 - Determination of the height of the spark discharge orientation

Starting from the height of the orientation, a predominant deviation of the leader's trajectory in the direction of the grounded electrode is manifested. Thus, it becomes possible to determine the average height of the orientation by constructing an averaged trajectory based on photographs of the discharge [39]. In fig. 2.2 the dependence of the orientation height (H_0) on the length of the discharge gap (S) is plotted for positive voltage pulses with different front durations. The value of H_0 coincides with the length of the gap S only with steep voltage pulses. With mild pulses, the H_0 / S ratio decreases the more the interval is longer.

Experiments showed that in all examined intervals, the orientation height is equal to the length of the streamer zone of the leader at the moment of transition to the through phase of the discharge (see Fig. 2.2). This gives reason to believe that, at least for a positive spark, the beginning of orientation practically coincides with the moment of transition to the through phase. For a negative spark, we can also talk about the approximate equality of the length of the streamer zone and the orientation height [36, 39]. However, the accuracy of determining the height of the orientation is insufficient in order to unambiguously link the beginning of the orientation here with the transition

of the discharge into the through phase or with the beginning of the development of the opposite leader, which can occur at a negative voltage shortly before the through phase.

Orientation of the leader channel in the through phase is apparently due to the falling current-current characteristic of the discharge in this phase. In such a situation, the direction of the leader channel is determined by those branches of the streamer zone that previously came into contact with the grounded electrode. However, the possibility is not excluded that in the intervals, which are much more examined, and especially with the negative polarity of the descending leader, the orientation will begin earlier due to the intensive development of the opposing leaders.

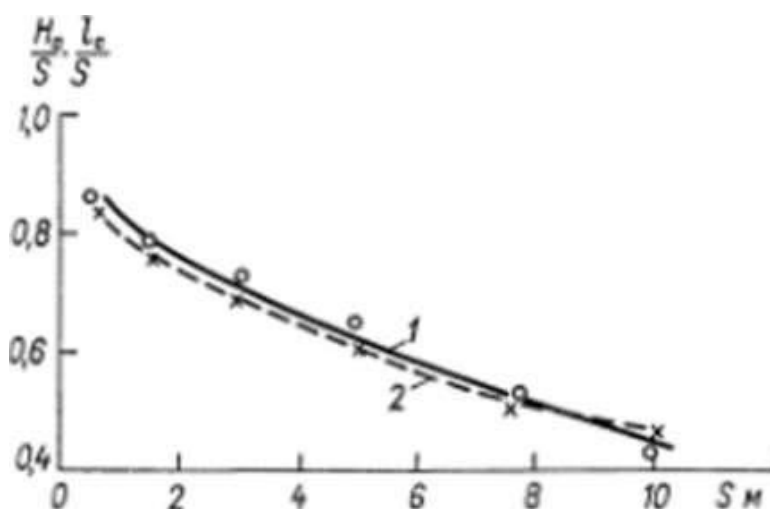


Figure 2.2 - Comparison of orientation height (H_0) and streamer zone length (l_c) for a positive spark in gaps of length (S).

In laboratory conditions, when $S / h > 5$, and the length of the streamer zone significantly exceeds the height of the grounded electrode h , the orientation height H_0 depends little on the shape of the top of the grounded electrode.

In many countries, the "electrogeometric model" is used to determine the protective properties of lightning conductors, the method was developed and proposed by the research committee No. 33 of SIGRE in 1975

The method is based on the idea that that when the leading channel approaches the ground object, the opposite discharge channel begins to develop, which causes a

lightning strike to the object. The shortest distance between the head of the leader and the point of impact at the moment of the onset of the counter discharge is called the orientation distance H_o . This distance is greater, the greater the voltage between the head of the leader and the grounded object, which means the greater the charge of the leader and the higher the maximum value of the lightning current passing through the affected object. The orientation distance depends on the lightning current in the first component of the strike and is determined by the empirical formula [40]

$$H_o = 2 I_l + 30 (1 - e^{-I_l/6,8}), \quad (2.1)$$

where, H_o is the height of lightning orientation in m;

I_l - lightning current in kA.

Using the given value of H_o , it is possible to build a zone of protection of one or another lightning conductor. In fig. 2.3 shows the construction of the rod lightning conductor protection zone ($h < H_l$).

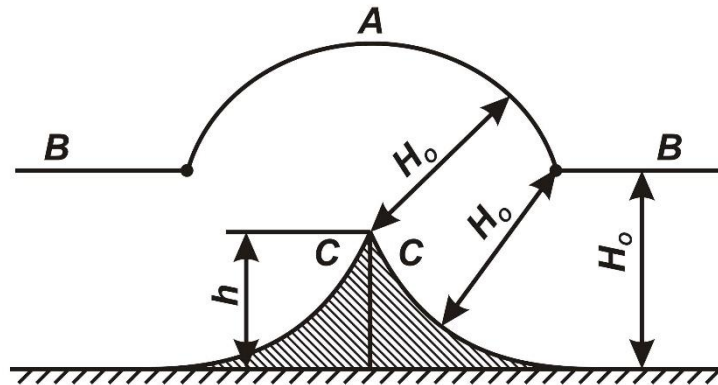


Figure 2.3 - Section of the protection zone with a lightning rod of height h at $H_o > h$

If the leader reaches surface A (Fig. 2.3), the lightning strikes the top of the lightning conductor. If it reaches surface B (Fig. 2.3), then the impact hits the ground. The object located below the surface C (Fig. 2.3). is located in the protection zone of the lightning conductor [40]. The probability of an object being struck by lightning (probability P of lightning breaking into the protection zone) is determined by the probability of the lightning current, which according to (2.1) corresponds to a certain

value of H_o adopted during the construction of the protection zone. For example, you need to set the dimensions of the protection zone with a reliability of $1 - P = 0.9$. For the first components, descending negative lightning with a probability of 0.9 corresponds to $I_l = 10$ kA. According to (2.1), we get the orientation distance:

$$H_o = 2 \cdot 10 + 30 (1 - e^{-10/6,8}) = 43 \text{ m.}$$

For lightning current $I_l = 20$ kA, the orientation height will be equal to:

$$H_o = 2 \cdot 20 + 30 (1 - e^{-20/6,8}) = 68 \text{ m.}$$

Methodology for calculating damage to PL by lightning

The methodology was developed at ENIN named after AHEM. Krzhizhanovsky in the second half of the last century and has proven itself well in the practice of lightning protection. In its simplest form, it considers the probabilities of overlapping the elementary gaps formed by the head of the lightning channel at the level of the orientation height H_o , the protected object, the height h_o , the lightning conductor height h_b , and the ground surface. At the same time, it is taken into account that due to the statistical spread of the electrical strength, any of the gaps can be covered with a certain probability, and not only the shortest one [41].

The point of lightning strike is established as a result of two independent events: the orientation process, during which the probability of lightning movement to the lightning rod-object system, rather than the earth's surface, is determined, and the selection process. The latter determines the probability of contact of the lightning channel with the object, and not with the lightning conductor. Both processes begin after the channel head of the descending leader descends to the level of the orientation height.

Laboratory model experiments together with theoretical studies, using the experience of observing high-rise objects such as the Ostankino TV tower in Moscow and the international experience of operating PL classes with a voltage of up to 500 kV, showed that a satisfactory mathematical description of both the process of orientation and selection is the same type of expressions, based on the normal distribution law of breakdown voltages of ultra-long air gaps [42 - 45]. If we put the

average values of the breakdown voltages in such gaps as equal (which is fully justified given their extremely long length), then the upper bounds of the probability integrals for the orientation functions $F(r)$ and selection $M(r)$ can be determined through geometric dimensions:

$$F(r) = \frac{1}{2} \cdot \left(1 - \sqrt{\frac{2}{\pi}} \int_0^{A_{op}} e^{-x^2/2} dx \right) \quad (2.2)$$

$$A_{op} = \frac{\sqrt{r^2 + (H_0 - h_0)^2} - H_0}{\sigma_{op} \cdot \sqrt{r^2 + (H_0 - h_0)^2 + H_0^2}} \quad (2.3)$$

$$M(r) = \frac{1}{2} \cdot \left(1 - \sqrt{\frac{2}{\pi}} \cdot \int_0^{A_{op}} e^{-x^2/2} dx \right) \quad (2.4)$$

$$A_1 = \frac{d_0 - d_0}{\sigma_{op} \cdot \sqrt{d_0^2 + d_0^2}} \quad (2.5)$$

Here, $F(r)$ and $M(r)$ are, respectively, the probability of orientation in the direction of the lightning rod-object system and the probability of selecting the impact point on the surface of the object;

r is the horizontal displacement distance from the object to the lightning;

H_0 is the height of lightning orientation,

$$d_l = \sqrt{(H_0 - h_l)^2 + r^2} \quad (2.6)$$

the shortest distance from the top of the lightning conductor to the head of the lightning channel at the height of orientation at the height of selection h_l ;

$$d_l = \sqrt{(H_0 - h_0)^2 + (r - a)^2} \quad (2.7)$$

- a similar distance to an object with a height of h_0 when the distance between it and the lightning conductor is equal to a .

The values of the standard of orientation (S_{or}) and the standard of selection (S_{sel}) characterize the statistical properties of the processes of orientation and selection in

relative units. The first of these parameters has a very specific physical meaning and is a standard for the spread of breakdown voltages of ultra-long intervals reduced to 50% of the breakdown voltage ($S_{or} \sim 0.1$). The value of the selection standard is fundamentally less than the orientation standard due to the mutual influence of the discharge processes in the elementary gaps of the multi-electrode system [45 - 49]. As a result of this influence, which amplifies any random statistical variation, the choice becomes more deterministic. As a result, as the distance between the tops of the grounded electrodes D decreases (for example, between the lightning conductor and the object), the value of S_{sel} decreases. Summarizing the experience of lightning conductors of various types allows obtaining an empirical calculation expression

$$S_{sel} = 7 \cdot 10^{-3} + 8 \cdot 10^{-5} D, \quad (2.8)$$

The product of probabilities $M(r) F(r)$ determines the probability of a lightning strike from point r to the protected object, bypassing the lightning rod. To determine the total expected number of lightning strikes, you need to integrate this application over the entire orientation plane, since the occurrence of lightning at any point is equally likely. Then the result of integration should be multiplied by the density of lightning discharges for this area n_l . In the simplest case, in the presence of radial symmetry,

$$N_{pl} = 2 \cdot \pi \cdot n_l \cdot \int_0^\infty M(r) \cdot F(r) \cdot r dr \quad (2.9)$$

A set of formulas similar to (2.2) - (2.9) can be extended to any arbitrarily complex system of lightning conductors and objects, if operated with the shortest distances to the ground, to the set of protected structures and to the set of lightning conductors. At the same time, both the objects of protection and the lightning conductors that protect them can be of any shape and any size, and the shortest distances and positions of the points on the grounded system, by which they are determined, will depend on the coordinates of the head of the lightning conductor x, y in orientation plane.

During the construction of protection zones in domestic regulatory documents, a constant value of the orientation standard $S_{or} = 0.1$ was adopted, and the orientation height was considered proportional to the height of the lightning protection system

$$H_o = 5h_l [16, 19].$$

If the intensity of thunderstorm activity at the location of the object being protected is known, a calculation program that implements a statistical technique that allows you to calculate the expected number of lightning strikes to the object during a given period of operation and determine the reliability of protection using an arbitrary system of lightning conductors of the most different heights and configurations.

The static method was used in the construction of all lightning conductor protection zones in national regulatory documents. For this purpose, you can, for example, choose the following calculation procedure. The expected number of lightning strikes in a lightning rod of a given height and in a circle on the surface of the earth is calculated. A series of successive approximations is the radius of the circle, at which the probability of lightning discharge to it is equal to the permissible value for the determined zone. This is how the radius of protection at ground level is determined. The procedure is then repeated sequentially for a series of increasing heights.

Basics of conducting a full factorial experiment

To carry out experimental research on the damage of PL and PPL by direct lightning strikes, we chose the method of conducting a full-factor experiment, which allows us to determine the dependence of the studied parameter on the influencing factors, based on regression analysis.

After the object of research and the optimization parameter have been selected, it is necessary to include in consideration all significant factors that can affect the process. If any significant factor is not taken into account, it can lead to unpleasant consequences. So, if the unaccounted factor fluctuated arbitrarily - assumed random values that were not controlled - this will significantly increase the error of the experiment. When maintaining the factor at some fixed level, a wrong idea of the optimum can be obtained, since there is no guarantee that the fixed level is optimal [50 - 59].

The number of different states of the object p^k , where p is the number of levels, and k is the number of factors. The more factors, the more experiments. Indeed, the number

of experiments grows exponentially. The dimensionality of the factor space increases, and mathematicians in such cases speak of the "curse of dimensionality".

If the number of factors is more than fifteen, it is necessary to turn to the methods of screening out insignificant factors. Here you can use the formalization of a priori information, the random balance method, Plackett-Bermap plans, etc. Sometimes these plans are used with fewer factors.

Determination of factors

A factor is a measured variable that assumes a certain value at some point in time. Factors correspond to methods of influence on the research object [49].

Just like an optimization parameter, each factor has a scope. We will consider the factor to be given if the area of its definition is specified together with its name. The field of definition means the set of all values that, in principle, this factor can take. It is clear that the set of values of the factor, which is used in the experiment, is a subset of the set of values that form the domain of definition.

The definition area can be continuous or discrete. However, in those experimental design tasks that we are going to consider, discrete domains of definition are always used. Thus, for factors with a continuous definition area, such as temperature, time, amount of substance, etc., discrete sets of levels are always selected. In practical tasks, the definition of factors is usually limited. Restrictions can be of a fundamental or technical nature. [49, 52]

Let's classify factors depending on whether the factor is a variable that can be quantified: measured, weighed, titrated, etc., or it is some variable characterized by qualitative properties.

Factors are divided into quantitative and qualitative. Quality factors are different substances, different technological methods, devices, performers, etc.

Although qualitative factors do not correspond to a numerical scale in the sense that it is understood for quantitative factors, it is possible to construct a conditional ordinal scale that corresponds to the levels of a qualitative factor of a number of a natural series, that is, produces coding. The order of the levels can be arbitrary, but after coding

it is fixed.

The optimization parameter is measured at the end of the last stage. In the previous stages, the initial parameter is not measured: the necessary analytical techniques are not available. Other reasons are possible, for example, the optimization parameter of a separate stage contradicts the common goal of optimization. But it would be wrong to think that in all cases, when optimizing multi-stage processes, all stages should be considered as a whole. Very often, the optimization of individual stages is completely justified and obvious. [48]

Thus, the planning of the experiment can include factors related to different stages, but it is not necessary in all cases.

Requirements for factors when planning an experiment

Factors must be controlled when planning an experiment. This means that the experimenter, having specified the desired value of the factor, can keep it constant throughout the experiment, that is, can control the factor. This is the peculiarity of the "active" experiment. It is possible to plan an experiment only if the levels of factors obey the will of the experimenter.

Air temperature is an uncontrollable factor. We have not yet learned how to make custom weather. And only those factors that can be controlled can participate in planning - set and maintain at the chosen level during the experience or change according to a given program. In this case, it is impossible to control the temperature of the surrounding environment. It can only be controlled. [49, 54]

In order to accurately determine the factor, you need to specify the sequence of actions (operations) with the help of which its specific values (levels) are set. Such definition of the factor will be called operational. So, if the factor is the pressure in some device, then it is absolutely necessary to indicate at what point and with which device it is measured and how it is set. The introduction of an operational definition provides an unambiguous understanding of the factor.

The selection of the dimension of the factor and the accuracy of its fixation are connected with the operational definition. We are used to believe that choosing the

dimension of the factor does not pose any particular difficulties. The experimenter has a good idea of which dimension to use. This is true in cases where there is an established tradition, built measuring scales, devices, created standards, etc. This is the situation when measuring temperature, time, pressure, etc. But it happens that the choice of dimensions turns into a very difficult problem the choice of measuring scales, the complexity of which is far beyond the scope of our consideration. [48, 55]

Replacing one measurement scale with another is called a conversion of scales. It can be used to simplify the object model.

The accuracy of factor measurement should be as high as possible. The degree of accuracy is determined by the range of changes in factors. When studying a process that lasts tens of hours, there is no need to take into account fractions of a minute, and in fast processes it is necessary to take into account, perhaps, fractions of a second. If the factors are measured with a large error or the feature of the research object is such that it is difficult to maintain the value of the factors at the chosen level (the level of the factor "floats"), then the experimenter should turn to confluent analysis.

Factors must be direct influences on the object. Factors must be unique. It is difficult to control a factor that is a function of other factors. But planning can also involve complex factors, such as the ratio between components, their logarithms, etc.

The need to introduce complex factors arises when you want to present the dynamic features of the object in a static form. Let, for example, you need to find the optimal mode of temperature rise in the reactor. If it is known about the temperature that it should increase linearly, then as a factor instead of a function (in this case linear) you can use the tangent of the angle of inclination, i.e. the gradient. The situation is complicated when the output temperature is not fixed. Then it has to be introduced as another factor. For more complex curves, it would be necessary to introduce a larger number of factors (high-order derivatives, coordinates of special points, etc.) [49, 58]. Therefore, it is advisable to use a complex qualitative factor - the curve number. Different variants of the curves are considered as levels. These can be various modes of heat treatment of alloys, transient processes in control systems, etc. We have shown how a complex factor-function can be represented using simple single-valued factors.

Such requirements to the factors in the planning of the experiment, such as controllability and ambiguity, are not fulfilled.

Requirements for a set of factors

When planning an experiment, several factors usually change at the same time. Therefore, it is very important to formulate the requirements for a set of factors. First of all, the requirement of compatibility is put forward. Compatibility of factors means that all their combinations are feasible and safe. Ego is a very important requirement. Imagine that you acted recklessly, ignored the requirement of compatibility of factors and planned such conditions of experience that could lead to an explosion of the installation or tarring of the product. Agree that such a result is very far from the goals of optimization.

The incompatibility of factors can be observed at the borders of the areas of their definition. You can get rid of it by reducing areas. The situation is complicated if the incompatibility is found within the definition areas. One of the possible solutions is the division into subareas and the solution of two separate tasks [49, 56].

When planning an experiment, the independence of factors is important, that is, the possibility of setting a factor at any level, regardless of the level of other factors. If this condition is impossible, then it is impossible to plan the experiment. So, we came to the second requirement - the absence of correlation between factors. The requirement of non-correlation does not mean that there is no relationship between the values of the factors. It is enough that the relationship is not linear.

Examples of factors

In this section, we have already given examples of factors related to organic chemistry and polymers. And now let's move on to other areas, remembering Newton's saying that examples are as instructive as rules.

Fields of practical application of experiment planning are extremely diverse: energy, chemistry, metallurgy, biology, medicine, mineral enrichment, food and textile industry, military affairs, etc. [51 - 53].

Experiment planning is also used in several unexpected areas of research, such as gerontology (the science of longevity), in the classification of ancient pottery samples, in baking and tobacco production. Factors also change depending on the objects of research.

A complete factorial experiment of type 2^k

The first stage of planning an experiment to obtain a linear model is based, as we agreed, on the variation of factors at two levels. In this case, if the number of factors is known, it is possible to immediately find the number of experiments necessary to implement all possible combinations of factor levels. A simple formula is used for this: $L' = 2^k$, where L' is the number of experiments, k - the number of factors, 2 - the number of levels. In general, an experiment in which all possible combinations of factor levels are implemented is called a full factorial experiment. If the number of levels of each factor is equal to two, then we have a complete factorial experiment of type 2^k .

It is not difficult to write all combinations of levels in an experiment with two factors. We will remind that in the planning of the experiment coded values of the factors are used: +1 and -1 (often units are omitted for ease of writing). The conditions of the experiment can be written in the form of a table, where the rows correspond to different experiments, and the columns correspond to the values of the factors. We will call such tables experiment planning matrices [48 - 52].

The planning matrix for two factors is shown in table. 2.1. Each column in the planning matrix is called a column vector, and each row is called a row vector.

Table 2.1 - Experiment planning matrix 2^k

Experiment number	X_1	X_2	Y	Experiment number	X_1	X_2	Y
1	-1	-1	Y_1	3	-1	+1	Y_3
2	+1	-1	Y_2	4	+1	+1	Y_4

Thus, in the table 2.1 we have two column vectors of independent changes and one column vector of the optimization parameter. What is recorded in this table in algebraic form can be represented geometrically. Let's find a point corresponding to the main level in the definition area of the factors, and draw new coordinate axes parallel to the axes of the natural values of the factors through it. Next, let's choose the scales along the new axes so that the interval of variation for each factor is equal to one. Then the conditions for the experiments will correspond to the top of the square, the center of which is the main level, and each side is parallel to one of the coordinate axes and is equal to two intervals. The numbers of the vertices of the square correspond to the numbers of experiments in the planning matrix. The area bounded by the square is called the experimental area. Sometimes it is more convenient to consider the area of the experiment as the area bounded by the circle that describes the square. In interpolation tasks, the area of the experiment is the area of expected values of Y .

Writing a planning matrix, especially for many factors, is cumbersome. To shorten it, it is convenient to enter conventional letter designations of lines.

It is done in the following way. The serial number of the factor corresponds to the lower case letter of the Latin alphabet: x_1 — a, x_2 — б, ... etc. If now Latin letters are written for the row of the planning matrix, only for the factors located at the upper levels, then the conditions experience will be given unambiguously. An experiment with all factors at the lower levels will be denoted by (1). The planning matrix together with the adopted letter designations is given in the table. 2.2.

Now, instead of a full record of the planning matrix, only letter designations can be used. Below is the letter record of another plan: *c, b, a, abc, (-), bc, ac, ab*. The planning matrix is given in table. 2.3.

Thus, we constructed a complete factorial experiment of 2^3 . It has eight experiments and includes all possible combinations of the levels of the three factors.

Table 2.2 - Experiment planning matrix 2^k

Experiment number	X1	X2	Experiment number	Y
1	-1	-1	(1)	Y1
2	+1	-1	A	Y2
3	-1	+1	B	Y3
4	+1	+1	AB	Y4

Table 2.3 - Experiment planning matrix 2^k

Experiment number	X1	X2	X3	Letter designations of lines	Y
1	-1	-1	+1	c	Y1
2	-1	+1	-1	b	Y2
3	+1	-1	-1	a	Y3
4	-1	+1	+1	abc	Y4
5	-1	-1	-1	(-)	Y5
6	+1	+1	-1	bc	Y6
7	+1	-1	+1	ac	Y7
8	+1	+1	+1	ab	Y8

Table 2.4 - Construction of the planning matrix of experiment 2^k

Experiment number	a	b	c	Y	Experiment number	a	b	c	Y
1	—	—	+	Y1	5	—	—	—	Y4
2	—	+	+	Y2	6	—	+	—	Y5
3	+	—	+	Y3	7	+	—	—	Y6
4	+	+	+	(-)	8	+	+	-	Y7

If for two factors, all possible combinations of levels are easy to find by direct enumeration (or simply memorized), then with the growth of the number of factors, there is a need for some method of constructing matrices. Of the many possible, three methods are usually used, based on the transition from matrices of lower dimension to matrices of higher dimension. Let's consider the first one. When adding a new factor, each combination of levels of the original plan occurs twice: in combination with the lower and upper levels of the new factor. From here, a technique naturally appears: write down the initial plan for one level of the new factor, and then repeat it for another level. This is how it looks when moving from experiment 2^k to 2^8 (table 2.4): in table 2.2.

This technique extends to the construction of matrices of any dimension [49, 52].

Let's consider the second method. To do this, we will introduce the rule of matrix column multiplication. When multiplying two columns of the matrix in order, the product of units with the same signs gives +1, and those with different names give -1. Using this rule, for the case we are considering, we will get a column vector of the product $x^i y^j$ the original plan. Next, we will repeat the original plan once again, and in the output column we will change the signs to the opposite

This technique can also be transferred to the construction of matrices of any dimension, but it is more complicated than the first.

The third technique is based on the rule of alternation of signs. In the first column, the signs change one after the other, in the second column they alternate by two, in the third - by 4, in the fourth - by 8, etc. according to powers of two. If in the table 2.4 swap the columns for x_1 and x_2 , then the required matrix will be obtained.

By analogy with the full factorial experiment 2^k , it is possible to give a geometric interpretation of the full factorial experiment 2^5 . The geometric interpretation of the full factorial experiment 2^3 is a cube, the coordinates of the vertices of which determine the conditions of the experiments.

If you place the center of the cube at the point of the main level of the factors, and choose the scales along the axes so that the interval of variation is equal to one, then you will get a cube. The cube defines the domain of the experiment, and the center of the cube is its center.

Obtaining similarity criteria based on the second similarity theorem

Obtaining similarity criteria by the method of dimensional analysis based on the description of the physical process. In the general case, the dependence takes into account all the connections between the parameters of the process and the elements of the system in which this process takes place, it can be written in the form

$$f(P_1, \dots, P_i, \dots, P_k, \dots, P_s, \dots, P_m) = 0, \quad (2.10)$$

where $P_1, \dots, P_m$ are parameters characterizing the investigated process

Equation (2.10) is complete and, therefore, homogeneous, so all the parameters included in it can be expressed in relative units, that is, in fractions of some selected values $P_1, \dots, P_m$ (2.10) can be written as follows:

$$f\left(\frac{P_1}{P_{01}}, \dots, \frac{P_i}{P_{0i}}, \dots, \frac{P_k}{P_{0k}}, \frac{P_{k+1}}{P_{0k+1}}, \dots, \frac{P_s}{P_{0s}}, \dots, \frac{P_m}{P_{0m}}\right) = 0 \quad (2.11)$$

However, not all values of $P_1, P_2, \dots, P_{0m}$ can be chosen arbitrarily. For example, having arbitrarily chosen values that measure current and voltage, one cannot arbitrarily choose a value that measures resistance or power. It is possible to set the number of quantities that are chosen from the total set of quantities $P_1, P_2, \dots, P_{0m}$

arbitrarily, and find a way to select others by considering the system of units in which equation (2.11) is written, since the dimension formulas reproduce the dependence between physical quantities [49, 53].

Let $k = q$ basic units of measurement in the chosen system of units. Denoting them by $a, b, \dots, q$, we write down the expression of the units of measurement of all participants, that is, their dimension formulas:

$$\left. \begin{aligned} [p_1] &= [a^{\alpha 1} \ b^{\beta 1} \ ...q^{\xi 1}] = [p_{01}]; \\ \\ [p_i] &= [a^{\alpha i} \ b^{\beta i} \ ...q^{\xi i}] = [p_{0i}]; \\ \\ [p_k] &= [a^{\alpha k} \ b^{\beta k} \ ...q^{\xi k}] = [p_{0k}]; \\ \\ [p_s] &= [a^{\alpha s} \ b^{\beta s} \ ...q^{\xi s}] = [p_{0s}]; \\ \\ [p_m] &= [a^{\alpha m} \ b^{\beta m} \ ...q^{\xi m}] = [p_{0m}], \end{aligned} \right\} \quad (2.12)$$

where $\alpha, \beta, \dots, \xi$ are real numbers

It should be noted that some measurement units $[p_{01}]$, ..., $[p_{0k}]$ are independent of each other. This means that the dimension formula of these units cannot be represented as a function (obtained by multiplication or division) of the dimension formulas of other independent units. At the same time, a sign of independence is the inequality of zero of at least one determinant D , composed of exponents of degrees a , b , ..., q in the dimension formulas for $[p_{01}]$, ..., $[p_{0k}]$ included in (2.12).

Further considerations will be made in relation to the case when $k = q$ since k units of measurement are independent, the other $m - k$ units of measurement will be their functions

[illegible]

By substituting the expressions (2.15) into the last $m - k$ equations of the system (2.12) from the $(k + 1)$ -th to the m -th, we will get $m - k$ expressions for the quantities involved in the process and now represented by arbitrarily chosen quantities $p_{01}, \dots, p_{0k}$. For example, for p_{0k+1} we have

$$[p_{0k+1}] = [p_{01}^{\alpha_{k+1}}]^{\frac{A_{11}}{D}} \dots [p_{0k}^{\alpha_{k+1}}]^{\frac{A_{k1}}{D}} [p_{01}^{\beta_{k+1}}]^{\frac{A_{12}}{D}} \dots$$

$$\dots [p_{01}^{\beta_{k+1}}]^{\frac{A_{k2}}{D}} \dots [p_{01}^{\xi_{k+1}}]^{\frac{A_{1k}}{D}} \dots [p_{0k}^{\xi_{k+1}}]^{\frac{A_{kk}}{D}} \quad (2.17)$$

For any value from p_{0k+1} to p_{0m} , that is, for p_{0s} , where $s = k+1, \dots, m$, you can write the corresponding expressions. Further, after grouping in the right-hand parts of the quantities with the same subscripts on the basis of (2.17), we obtain the desired functional relations $\psi_s(s = k + 1, \dots, m)$ in (2.13):

$$[p_{0s}] = [p_{01}]^{D_{1s/D}} \dots [p_{0i}]^{D_{is/D}} \dots [p_{0k}]^{D_{ks/D}} \quad (2.18)$$

or

$$[P_{0s}] = [P_{01}]^{D_{1s/D}} \dots [P_{0i}]^{D_{is/D}} \dots [P_{0k}]^{D_{ks/D}} \quad (2.19)$$

where $D_{i,s}$ is the determinant obtained from D by replacing its i -th row with a row composed of exponents of the power in the basic units in the dimension formula of the s -th unit of measurement, that is, with the row $\alpha'_s, \beta'_s, \xi'_s$

$$\alpha'_s = \frac{D_{1s}}{D}; \dots; \gamma'_s = \frac{D_{1s}}{D}; \dots; \xi'_s = \frac{D_{1s}}{D}.$$

if among the m quantities $P_{01}, \dots, P_{0m}$ participating in equation (2.11) there are k independent ($P_{01}, \dots, P_{0i}, \dots, P_{0k}$) chosen arbitrarily, then the other $m - k$ quantities ($P_{0p+1}, \dots, P_{0s}, \dots, P_{0m}$) are products of selected independent quantities of the corresponding powers $\alpha'_s, \dots, \xi'_s$, de $s = k+1, \dots, m$ i.e.

$$P_{0s} = P_{01}^{y_1} \dots P_{0i}^{y_i} \dots P_{0k}^{y_k} \quad (2.20)$$

where $y_i = D_{is}/D$

According to (2.20), equation (2.11) will take the form

$$f\left(\frac{P_1}{P_{01}}, \dots, \frac{P_1}{P_{01}}, \dots, \frac{P_1}{P_{01}}, \dots, \frac{P_{k+1}}{p_{01}^{x_1} \dots p_{0i}^{x_i} \dots p_{0k}^{x_k}}, \dots, \frac{P_s}{p_{01}^{y_1} \dots p_{0i}^{y_i} \dots p_{0k}^{y_k}}, \dots, \frac{P_m}{p_{01}^{zx_1} \dots p_{0i}^{z_i} \dots p_{0k}^{z_k}}\right) = 0 \quad (2.21)$$

Since k values of P_0 are independent, they can be chosen arbitrarily and accepted, for example, $P_{01} = P_1, P_{02} = P_2, \dots, P_{0k} = P_k$. Further assuming $x_1 = \alpha'_{k+1}, \dots, x_k = \xi'_{k+1}, y_1 = \alpha'_s, \dots, y_k = \xi'_s, z_1 = \alpha'_m, \dots, z_k = \xi'_m$; we will get

$$f\left(1, 1, \dots, 1, \frac{P_{k+1}}{p_1^{x_1} \dots p_i^{x_i} \dots p_k^{x_k}}, \dots, \frac{P_s}{p_1^{y_1} \dots p_i^{y_i} \dots p_k^{y_k}}, \dots, \frac{P_m}{p_1^{zx_1} \dots p_i^{z_i} \dots p_k^{z_k}}\right) = 0 \quad (2.22)$$

Recall that the units of measurement of the numerators and denominators of all relations

$$\frac{P_{k+1}}{p_1^{x_1} \dots p_i^{x_i} \dots p_k^{x_k}}, \dots, \frac{P_s}{p_1^{y_1} \dots p_i^{y_i} \dots p_k^{y_k}}, \dots, \frac{P_m}{p_1^{zx_1} \dots p_i^{z_i} \dots p_k^{z_k}},$$

levels resulting from system (2.12) and the following statements. Thus, each of these relations is a relation between numbers and is therefore an abstract number. So, the original equation can be represented in the form

$$f\left(1, 1, \dots, 1, \frac{\{P_{k+1}\}}{\{P_1\}^{x_1} \dots \{P_k\}^{x_k}}, \dots, \frac{\{P_m\}}{\{P_1\}^{z_1} \dots \{P_1\}^{z_k}}\right) = 0 \quad (2.23)$$

or

$$f(1, 1, \dots, 1, \pi_1, \dots, \pi_{m-k}) = 0 \quad (2.24)$$

where

$$\pi_1 = \frac{\{P_{k+1}\}}{\{P_1\}^{x_1} \dots \{P_k\}^{x_k}}; \dots; \pi_s = \frac{\{P_s\}}{\{P_1\}^{x_1} \dots \{P_k\}^{x_k}}; \dots; \pi_{m-k} = \frac{\{P_m\}}{\{P_1\}^{z_1} \dots \{P_k\}^{z_k}} \quad (2.25)$$

or

$$\pi_{m-k} = \frac{P_m}{p_1^{\alpha'_m} p_2^{\beta'_m} \dots p_k^{\xi'_m}} \quad (2.26)$$

The units of measurement of the numerators and denominators in the expressions $\pi_1, \dots, \pi_s, \dots, \pi_{m-k}$ are equal, therefore

By substituting the basic units of measurement into the written equality, we get

$$a^{\alpha s} b^{\beta s} \dots q^{\xi s} = (a^{\alpha 1} b^{\beta 1} \dots q^{\xi 1})^{\alpha s} \dots (a^{\alpha 2} b^{\beta 2} \dots q^{\xi 2})^{\beta s} \dots (a^{\alpha k} b^{\beta k} \dots q^{\xi k})^{\xi s}$$

$$\left. \begin{aligned} \alpha_s &= \alpha_1 \alpha_s + \alpha_2 \beta_s + \alpha_k \xi_s; \\ \beta_s &= \beta_1 \alpha_s + \beta_2 \beta_s + \beta_k \xi_s; \\ &\dots\dots\dots \\ \xi_s &= \xi_1 \alpha_s + \xi_2 \beta_s + \xi_k \xi_s. \end{aligned} \right\} \quad (2.27)$$

We will show that the obtained ratios π are similarity criteria. Consider two similar processes described by complete equations with m parameters. We denote the parameters of the first process by the symbol P , and the second by R , and write the equations of these processes in the form (2.25)

$$f(1,1, \dots, 1, \frac{Rk+1}{R_1x_1}, \frac{Rk+1}{R_kx_k}, \dots, \frac{Rm}{R_1z_k}, \frac{Rm}{R_kz_k})=0 \quad (2.29)$$

$$R_1 = m_1 P_1, \dots, R_m = m_m P_m, \quad (2.30)$$

or

$$\frac{m^{k+1}}{m_1^{x_1} \dots m_k^{x_k}} = 1; \dots; \frac{m^m}{m_1^{z_1} \dots m_k^{z_k}} = 1 \quad (2.35)$$

It follows from (2.34) and (2.35) that

[illegible]

Therefore, the ratios π obtained as a result of reducing the equation of two similar processes to a dimensionless form turned out to be equal. Therefore, according to the first theorem of similarity, these relations are criteria of similarity. The obtained results can be extended to any number of similar processes.

The conducted analysis shows that the physical process is mathematically represented by the function of $m - k$ dimensionless ratios - similarity criteria π . Any equation that gives a relationship between m participating quantities, presented in a criterion form, being allowed for any similarity criterion (for example, π_1), allows to express it as a function of $m - k - 1$ similarity criteria [51] :

$$\pi_1 = f(\pi_2, \pi_3, \dots, \pi_{m-k}). \quad (2.37)$$

The values of the π criteria are the same for any number of similar processes occurring in different systems, the similar parameters of which are proportional. The ratio (2.37) is called the criterion equation. It shows that one of the $m - k$ similarity criteria is a function of the other $m - k - 1$ criteria. Thus, the number of values that determine the nature of the process in the criterion form of the record is reduced by $k + 1$. There are $m - k - 1$ independent criteria. In this case, it is $\pi_2, \pi_3, \dots, \pi_{m-k}$. The dependent criterion π_1 is fulfilled automatically when the independent criteria are met, which directly follows from (2.37).

Connection of similarity criteria found on the basis of the π -theorem and obtained from the analysis of equations. According to the first theorem, the criteria for the similarity of processes can be dimensionless relations of the members of the equation; at the same time, the number of similarity criteria is one less than the number of terms of the equation. This provision does not contradict the conclusions of the second theorem about the presence of only $m - k$ criteria, of which $m - k - 1$ are independent [52]. Indeed, if we consider any criterion of similarity obtained as a ratio of the members of the equation, for example φ_j/φ_n , then this ratio can in general be a function of all the parameters $P_1, \dots, P_m$ participating in the equation:

$$\varphi_j/\varphi_n = F(P_1, \dots, P_m).$$

However, the function $F(P_1, \dots, P_m)$ can be represented as a function of $m - k$ similarity criteria $\pi_1, \dots, \pi_{m-k}$:

$$\varphi_j/\varphi_n = F(\pi_1, \dots, \pi_{j-1}, \pi_{j+1}, \dots, \pi_{m-k}) = \pi_j.$$

Thus, the similarity criteria obtained directly from the complete equation (functional description) of the process coincide with the criteria obtained on the basis of the π -theorem.

Factors affecting PL damage

Lightning factors and structural features of power transmission lines can be attributed to the factors that affect damage.

As shown by studies [60], in most cases (up to 90%) lightning is negative, that is, it transfers a negative charge to the ground. A lightning discharge to the ground in the initial stage is a relatively slow-moving, dimly glowing channel (leader). The intensity of the electric field at its head is determined by the leader's own charges and are under clouds of accumulation of volume charges. The trajectory of the leader's movement at this stage is not related to earthly objects.

But as the leader descends, the accumulation of charges on the ground and elevated objects (q) begin to exert a greater influence. Starting from a certain height of

the leader's head, the orientation height (H_{oh}), the field strength in one of the directions is the greatest, and the leader is oriented to one of the ground objects. At the same time, high objects and areas of land with increased conductivity are mainly affected (selective damage) [61].

Counter-leaders develop from high objects towards the leader, the presence of which contributes to the orientation of the lightning on this object.

Rising above the surrounding terrain, the PL is affected by the discharges that develop directly above it.

The number of direct lightning strikes to the line depends on the density of lightning discharges to the ground, the distance between the extreme wires on the PL (D) and the length of the line (L), since we are considering a unit of PL length, the line length factor is not taken into account.

The probability of damage to a particular wire on the PL depends on such parameters as the distance between the extreme wires on the PL (D) and the height of the wires rising above each other (h).

The probability of damage to the PL by side discharges depends on the amplitude of the lightning current (I_l) and the height of the wire suspension (H_{sus}). The greater the lightning current, the greater the distance the lightning discharge is oriented to the PL [62].

Lightning with large currents occurs extremely rarely. Thus, lightning with currents of 200 kA occurs in 0.7 ... 1.0% of cases out of the total number of observed discharges. The number of cases of lightning strikes with a current of 20 kA is about 50%. Therefore, it is customary to present the value of the amplitudes of lightning currents in the form of probability curves (distribution functions), for which the probability of the appearance of lightning currents with the maximum value is plotted along the ordinate axis.

The main quantitative characteristic of lightning is the current that is supplied to the struck object. The lightning current (I_l) is characterized by the maximum value, the

average steepness of the front (α) and the duration of the pulse, which is equal to the time for the current to decrease to half the maximum value.

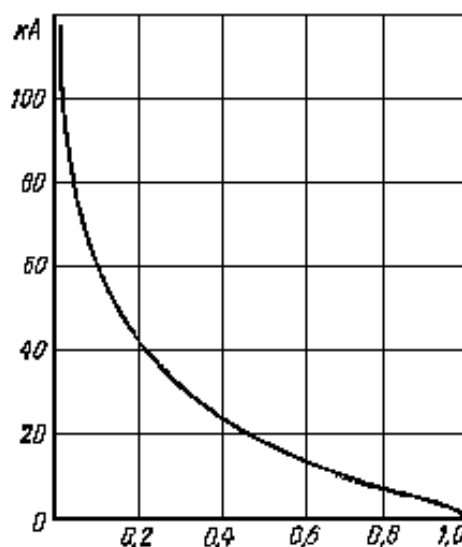


Figure 2.4 - Probability curves of lightning currents

When calculating lightning protection, the curve of Fig. 2.4.

The number of thunderstorm days per year or the total annual duration of thunderstorms in hours usually characterizes the intensity of thunderstorm activity. The latter characteristic is more correct, because the number of lightning strikes to the ground does not depend on the number of thunderstorms, but on their total duration [62].

The number of thunderstorm days or hours per year is determined on the basis of long-term observations of meteorological stations. The average duration of thunderstorms in one stormy day for the territory of Ukraine is 1.5 - 2 hours.

According to the available data, in areas with the number of thunderstorm hours per year $n = 30$ per 1 km² of the earth's surface is affected on average once every 2 years, i.e. the average number of lightning discharges per 1 km² of the earth's surface in 1 thunderstorm hour is 0.067. These data allow us to estimate the frequency of lightning strikes of various objects.

The functional dependence to be investigated has the following form:

$$f(I_l, \alpha, H_{oh}, D, H_{sus}, q, h) = 0 \quad (2.38)$$

When choosing a system of units, it is necessary to take into account the fact that electrical and mechanical parameters are involved in the described process. The most optimal is the LMTI system of units where: L is linear size (length), M is mass, T is time, I is current [52, 61].

The process of damage to overhead lines by direct lightning strikes is described by - 7 parameters, the dimension matrix of the parameters describing the researched process is given in table 2.5.

Table 2.5 - Dimensional matrix of parameters describing the process of PL lightning damage in the LMTI unit system.

Marking	L	M	T	I
I_l	0	0	0	1
A	2	1	-4	-1
H_{oh}	1	0	0	0
D	1	0	0	0
H_{sus}	1	0	0	0
Q	0	0	1	1
H	1	0	0	0

Let's choose arbitrarily four independent parameters, let the independent values for this measurement system be: $P_1 = H_{sus}$, $P_2 = \alpha$, $P_3 = q$, $P_4 = I_l$. The main condition of independence is the inequality of zero of the determinant composed of indicators, the basic units of which are included in the dimension matrix of the selected parameters.

$$P := \begin{pmatrix} 1 & 0 & 0 & 0 \\ 2 & 1 & -4 & -1 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$P = 1$$

$$|rank(P)| = 4$$

Since for the matrix P the determinant is not equal to zero and the rank is equal to 4, therefore, these parameters are truly independent. and the number of independent variables is chosen to be true ($k = 4$). Therefore, the number of similarity criteria ($m - k$) will be equal to 3. The general form of the similarity criteria will be determined by the expression:

$$\pi_1 = \frac{P_{K+1}}{P_1^{a_{k+1}} \cdot P_2^{b_{k+1}} \cdot \dots \cdot P_k^{e_{k+1}}} \quad (2.39)$$

The next task is to determine the dimensionality indicators $a_i, b_i, c_i \dots$ etc. To do this, we will express all the values included in the similarity criterion through the basic units of measurement and equate the indicators of the basic values of the same name in the numerator and denominator.

We defined similarity criteria for parameters that affect the damage of overhead lines.

The resulting criteria are as follows:

$$\pi_1 = \frac{H_{o\Box}}{H_{sus}} \quad (2.40)$$

$$\pi_2 = \frac{H_{o\Box}}{D} \quad (2.41)$$

$$\pi_3 = \frac{H_o}{\square} \quad (2.42)$$

The obtained criteria can be used in the construction of an experimental model for studying the susceptibility of overhead power lines of medium voltage classes to direct lightning strikes.

Construction of an experimental model for the study of radiation susceptibility of PL with protected and non-insulated wires

For consideration, we take lightning currents equal to 10 kA and 20 kA.

According to (2.1), the height of lightning orientation will be 43 m and 68 m, respectively.

Since we conduct tests for lines of medium voltage classes, we consider typical supports PM 10-1 for 6 kV lines and PS 35P-5M for 35 kV lines. The height of the wire suspension for the PM 10-1 support is 9 m, and for the PS 35P-5M support it is 15 m. The tested wires were SIP-3 1*50 - 20 and AS-50/8.

In the laboratory of ultra-high voltages of the National Technical University "Kharkiv Polytechnic Institute" a PL model was created, which allows simulating a line with non-insulated or shielded wires. This model makes it possible to perform experiments to determine the probability of a direct lightning strike in PPL and PL with different geometric parameters of the lines [50, 63 - 68].

As an experimental space, we chose a space measuring 1 m. Based on this, all the necessary dimensions of the studied experimental model were determined.

As a source of high voltage, a pulse voltage generator (PUG) with a maximum voltage of 2.4 MV was used, the appearance of which is shown in Fig. 2.6. The PUG is assembled according to a single-semiperiod scheme using 24 capacitors with a capacity of 0.25 μ F and a voltage of 100 kV. The PUG is powered through a 200 / 100,000 V step-up transformer. The PUG provides a standard form of lightning impulse with a front length of 1.2 μ s and a half-life of 50 μ s.

The general appearance of the model is shown in fig. 2.5.

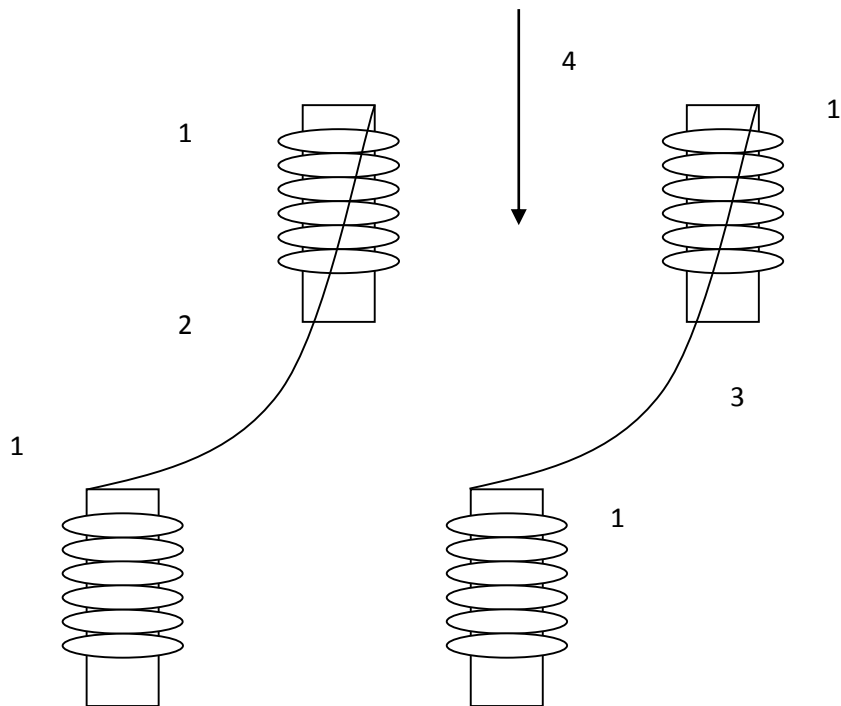


Figure 2.5 - General view of the model: 1 - support insulator, 2 - non-insulated wire, 3 - protected wire, 4 - electrode imitating lightning



Figure 2.6 – 2.4 MV impulse voltage generator

Thus, according to (2.40), (2.41) and (2.42), the height of the wire suspension will be equal to 0.2 m, for a line with a voltage of 6 kV and a lightning current of 10 kA. The height of the suspension of the electrode imitating lightning is 1 m.

CHAPTER 3. EXPERIMENTAL STUDY OF LIGHTNING SUSCEPTIBILITY OF PL AND PPL

Experimental confirmation of the constructed large-scale model on a sample of a 110 kV line

The approaches to modeling based on the height of lightning orientation obtained in Chapter 2 require experimental confirmation by comparing calculated and experimental data on the probability of lightning breaking through the cable protection [69 - 74]. The calculation of such probability was carried out on the basis of normative documents, which contain the calculation formula:

$$Lg P_{lb} = \frac{a \sqrt{h_{hs}}}{90} - 4 \quad (3.1)$$

where, P_{lb} is the probability of lightning breaking through the cable protection;

a – angle of protection of the lightning protection cable;

h_{hs} - the height of the suspension of the lightning protection cable.

Formula (3.1) is used in calculations of lightning resistance of PL with lightning protection cable. Therefore, in order to carry out experiments, we need to develop a model of a PL with cable protection and perform experiments to determine the probability of a lightning strike on the wire of such a PL. To check the reliability of the modeling method based on the height of the orientation, the values of the probability of lightning breaking through the cable protection of the PL at protection angles of 15, 20, 30 and 40 degrees were tested for coincidence. To create such a model, we used AS-50 brand wires for modeling phase wires and an enamel wire with a diameter of 2.5 mm as a lightning protection cable. The dimensions of the large-scale model were calculated based on the orientation height, which was assumed to be 1.2 m on the model, taking into account the design of the typical U 110-1 support, its diagram is presented in Fig. 3.1.

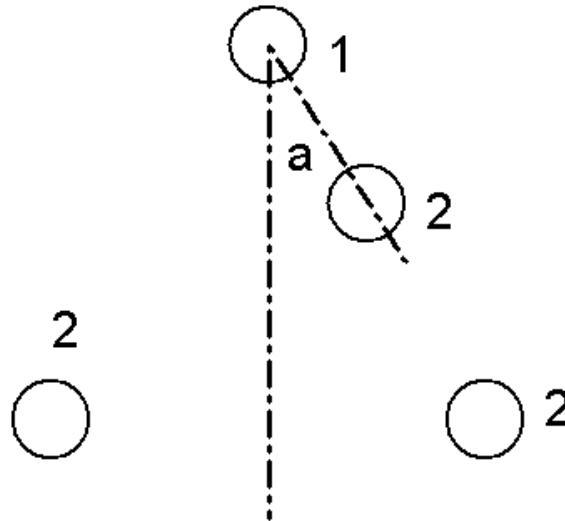


Figure 3.1 – 110 kV line model; a - angle of protection of the lightning protection cable; 1 – lightning protection cable; 2 - phase wires

As a voltage source, a 2.4 MV PUG, described in Chapter 2, was used. The PUG voltage was selected in such a way as to ensure a 98% probability of a breakdown of the gap between the electrodes, which simulates lightning - "ground". In order to achieve the acceptable accuracy of the experimental result in each series of tests for a defined angle of protection a , 100 tests were conducted for one position of the electrode simulating lightning.

The built experimental model had the following parameters: the electrode simulating lightning was located above the lightning protection cable and moved 0.3 m to a distance from the line axis equal to 0.9 m, the distance where there was a large number of lightning strikes to the "ground"; electrode height – 1.2 m; the height of the suspension of the lightning protection cable is 0.6 m: the height of the suspension of the phase wire is 0.55 m; the distance from the phase wire to the axis of the line changed according to the angle of protection, for 15° it was 0.08 m, for 20° - 0.11m, 30° - 0.18m, 40° - 0.26m.

Thus, 16 series of experimental studies were conducted to test all combinations. The obtained results for each series are shown in the table. 3.1.

Table 3.1 - The number of direct lightning strikes to the phase wire to determine the probability of lightning breaking through the cable protection at different locations of the lightning-imitating electrode

angle of protection, α	The electrode simulating lightning is located at a distance from the lightning protection cable, m			
	0	0,3	0,6	0,9
15°	0	0	0	0
20°	0	0	0	1
30°	0	0	1	4
40°	0	1	4	16

As can be seen from the results given in the table. 3.1, the probability of damage to the phase wire at a protection angle of 15° will be 0%, for 20° - 0.25%, 30° - 1.25%, 40° - 5.25%.

We compare the probabilities found experimentally with the probability calculated according to (3.1). The obtained results for comparison of calculation and experiments are shown in fig. 3.2.

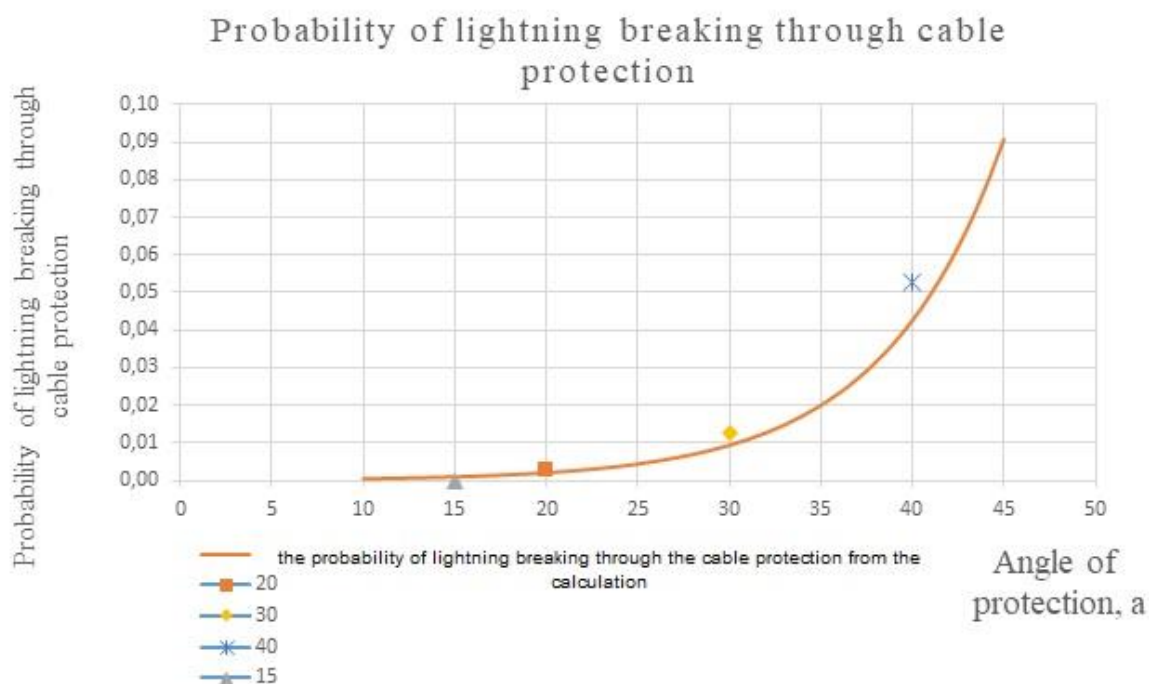


Figure 3.2 – the dependence of the probability of lightning breaking through the cable protection on the protection angle

Comparison of table data. 3.1 and fig. 3.2 makes it possible to conclude that the largest error of the experiment is up to 10%. It is worth noting that the error grows with the increase in the value of the protective angle, this can be explained by different approaches in modeling the process of PL lightning damage. When the expression (3.1) was defined, the modeling was performed on the basis of only geometric similarity, in our case, the height of the lightning orientation was used as the main modeling criterion. The obtained results indicate a fairly good match between the theoretical and experimental data, which makes it possible to assert the adequacy of the modeling principle proposed in the work.

Experimental studies of susceptibility of PL and PPL

Lightning protection of overhead power lines of medium voltage classes has significant differences from protection of PL 110 - 750 kV. For medium voltage classes, the problems of lightning protection are primarily due to the low electrical

strength of the linear insulation. It is generally accepted that almost any lightning will lead to the occurrence of overvoltages on the insulation sufficient for its overlap. The second factor affecting the lightning resistance of PLs is their small height. This causes a sufficiently small number of direct lightning strikes to PL wires [75]. Another specific difference of damage to PLs of medium voltage classes by lightning is a significant number of induced overvoltages, which lead to overlapping of PL insulation. This fact makes it necessary to take into account lightning resistance calculations.

In recent years, shielded wires have been widely used in the world. The use of such wires in the construction of a submarine, as was shown above, has a number of advantages. However, from the point of view of lightning protection, their use led to the need to use special means of lightning protection [76].

Many works by various researchers are devoted to the study of lightning protection of medium voltage class PLs, PLs with protected wires. However, all of them are based on well-known methods and are usually dedicated to the means of protecting wires from possible burns, which are due to the peculiarities of the existence of an arc on wires with an insulating coating [77 - 81]. The techniques themselves, which are obtained on the basis of processing operational experience and research on models, are not improved. Some researchers put forward hypotheses about a significant reduction or absence of damage to PLs with protected wires by direct lightning strikes. Such hypotheses are related to the fact that the conditions for the development of the counter conductor from the wire to the lightning channel are different from similar conditions for uninsulated wires. This assumption makes it possible to state that the number of direct lightning strikes to the PL wires will be significantly different for non-insulated and protected wires. At the same time, in the normative documents for calculating the lightning susceptibility of PL and PPL, it is recommended to calculate the lightning susceptibility of PPL in the same way as for PL, in this way, such a factor as the type of wire is not taken into account, that is, the value of the lightning resistance of non-insulated and protected wires is taken to be the same.

In order to study the issue of the difference in the number of direct lightning strikes in PLs with protected wires, we built a large-scale model of PLs with non-insulated and protected wires, and conducted studies of the probability of PL damage.

We conducted five series of experiments with different PL configurations, which allowed us to determine the difference in the probability of damage to non-insulated and protected wires.

The first series of experiments

In the first series of experiments, a comparison of the probability of a direct lightning strike on wires was performed for lines on which protected and non-insulated wires are located at the same time. To study lightning vulnerability, at the first stage, it is necessary to create equal conditions for damage to PL and PPL by a direct lightning strike.

The parameters of the model were determined in accordance with Chapter 2, that is, based on the height of the lightning orientation and had the following values: the electrode was located at a height of 1 meter from the surface of the "ground", at a height of 20 cm from the surface of the "ground" there were a protected and non-insulated wire, on at a distance of 90 cm from each other, an electrode imitating lightning was installed in the middle between the wires, 45 cm from each. When conducting experimental studies, a voltage source of 2.4 MV was used. The created experimental model, according to these parameters, is shown in Fig. 3.3 and fig. 3.4.



Figure 3.3 is a photograph of a large-scale model for the first series of experiments



Figure 3.4 is a photograph of damage to an uninsulated wire on a large-scale model during the first series of experiments

According to the result of 100 experiments, all the discharges got into the non-insulated wire. This result allows us to draw a conclusion about the different probability of damage to non-insulated and protected wires. The obtained results confirm the hypothesis about different mechanisms of damage to uninsulated and protected wires

by lightning and allow us to make assumptions about the increased lightning resistance of lines with protected wires due to the complication of the development of the counter conductor from the wire.

The second series of experiments

In order to test the hypothesis that protected wires are not affected by direct lightning strikes, we decided to complicate the vulnerability conditions for the protected wire. The second series of experiments was performed on a similar model of lines on which both protected and non-insulated wires are located. The main difference of this series of experiments was that the electrode simulating lightning was installed at a distance of 30 cm from the protected and 60 cm from the non-insulated one. Such an arrangement of the electrode that simulates lightning allows to investigate the probability of a direct hit to the line conductors when a lightning channel occurs in an arbitrary place in space. The parameters of the model had the same values as in the first series of experiments. The created experimental model, according to these parameters, is shown in Fig. 3.5.

Four series of experiments of 100 experiments each were performed, the results obtained are as follows: in two series of experiments, 70 blows were applied to an uninsulated wire and 30 blows to a protected one, in one 68 blows to an uninsulated wire and 32 to a protected one, and in the last 73 to non-insulated wire and 27 V protected.



Figure 3.5 is a photograph of a large-scale model for the second series of experiments

From the obtained results, it can be seen that the probability of a direct hit to the protected wire exists and, in the heart, is 30% of the total number of hits. Thus, it can be concluded that the probability of damage to a wire with an insulating coating is much lower than damage to an uninsulated wire. This is due to the fact that the insulating coating of the shielded wires does not provide an opportunity for the counter conductor to develop from the surface of the wire. Which significantly reduces the number of direct lightning strikes in PPL compared to PL. Also, this probability depends on the location of the lightning-imitating electrode.

The third series of experiments

In order to study the probability of a direct lightning strike in the PPL under the most severe conditions, when the electrode simulating lightning is located directly above the protected wire, we conduct a third series of experiments.

In the third series of experiments, a comparison of the probability of a direct lightning strike was made for lines on which both protected and non-insulated wires are suspended. The model parameters were similar to the first two experiments. And the electrode imitating lightning was installed above the protected wire. The experimental model shown in fig. 3.6.



Figure 3.6 is a photograph of a large-scale model for the third series of experiments

5 series of 100 experiments each were performed. In two of them, the probability of a direct hit to the protected wire was 50% of the total number of hits, in subsequent series the probability ranged from 47 to 51%. The obtained results confirmed the conclusion that the probability of damage by lightning to a protected wire, if there is also an uninsulated wire on the line, depends on the conditions for the development of the opposite leader and the location of the electrode simulating lightning.

Nevertheless, even under the most difficult conditions for a protected wire, the probability of its damage was 50%, which indicates an increased lightning resistance than that of an uninsulated wire.

Table 3.2 – Probability of damage to protected wires by a direct lightning strike at different locations of the lightning-imitating electrode

Number of series	The electrode simulating lightning is located at a distance from the protected and non-insulated wire		
	Intermediate, between protected and uninsulated (45 cm)	Closer to the shielded wire is 30 cm and 60 cm to the non-insulated one	Above the shielded wire, 90 cm to the uninsulated
1	0	27	47
2	-	30	50
3	-	32	48
4	-	30	51
5	-	-	50

As can be seen from the table. 3.2 the probability of damage to the protected wire depends on the location of the electrode simulating lightning. All things being equal, the probability of damage to an uninsulated wire is greater than that of a protected one.

The fourth series of experiments

In the fourth series of experiments, the probability of a lightning strike into a protected wire was determined at the same distances from the wire to the electrode simulating lightning and from the specified electrode to the "ground". The height of the electrode and wire suspension was the same as in the previous experiments. The experimental model shown in fig. 3.7.



Figure 3.7 is a photograph of the large-scale model for the fourth series of experiments

Four series of 100 experiments each were conducted. The probability of hitting a protected wire varied from 26% to 32% of the total number of hits. The obtained results well illustrate the presence of model spark strikes on the surface of the "earth", which can be a confirmation of the correctness of the selected scheme and methodology of experimental research.

The fifth series of experiments

When performing the fifth series of experiments, the probability of a lightning strike in an uninsulated wire was determined at the same distance from the wire to the electrode simulating lightning and from the specified electrode to the "ground". The experimental model shown in fig. 3.8. Conducting similar series of experiments is related to the comparison of damage probabilities of non-insulated and protected wires. Such a comparison is necessary to confirm the presence of differences in the damage mechanisms of protected and non-insulated wires and to take such differences into

account when calculating the lightning resistance of PL at the stage of making design decisions.

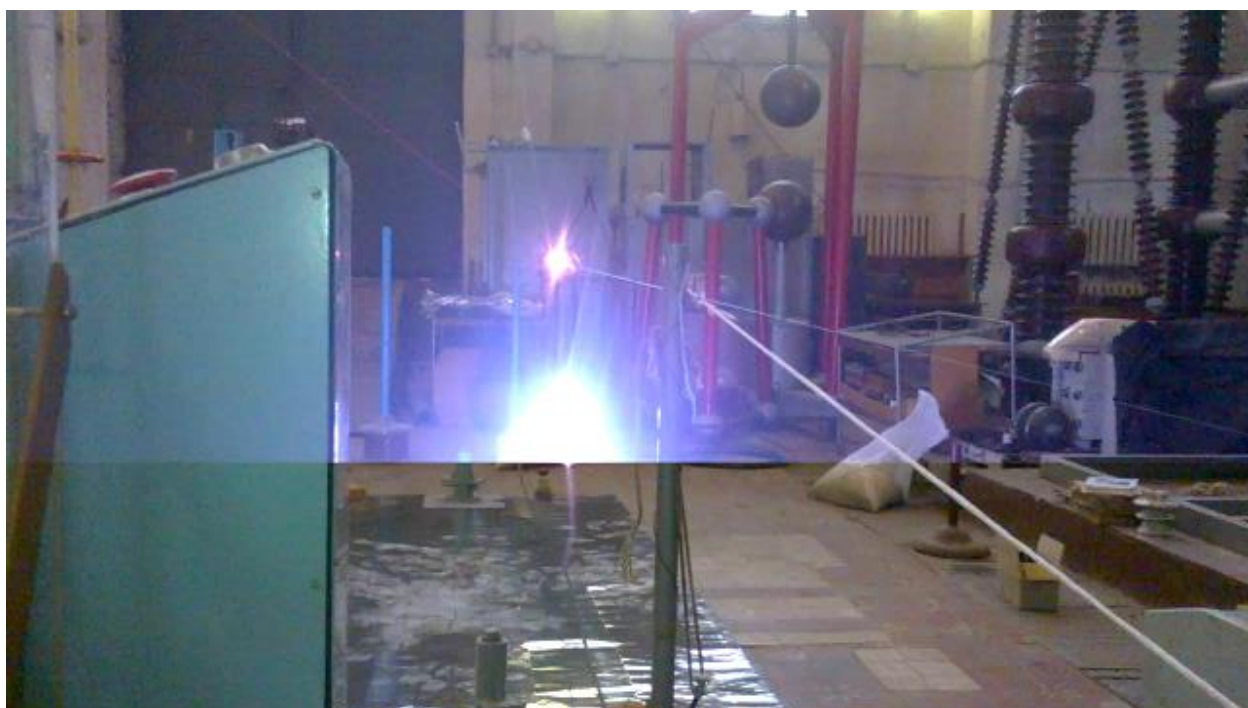


Figure 3.8 is a photograph of the large-scale model for the fifth series of experiments

The height of the electrode and wire suspension was the same as in the previous experiments. 3 series of 100 experiments each were conducted. The probability of hitting an uninsulated wire varied from 70% to 72% of the total number of hits. The obtained results allow us to draw a conclusion about significant differences in the damage probability values of protected and non-insulated wires. Such a difference allows us to suggest that the PL with protected wires has much better lightning resistance indicators than the PL with non-insulated wires.

Table 3.3 – Probability of damage to wires by a direct lightning strike with different types of wires.

Number of series	The lightning-imitating electrode is equidistant from the shielded or non-insulated wire to "ground"	
	Probability of damage to the protected wire	The probability of damage to an uninsulated wire
1	27	71
2	30	72
3	26	70
4	32	-

Conducting experimental studies to determine the zone of lightning capture by line wires

To conduct experimental research, according to the theory of conducting the experiment, we will build an experiment matrix, taking into account the factors affecting the process of damage to the overhead line by a direct lightning strike [81]. The main factors include the lightning current (I_l), the line voltage (U), and the type of wire (shielded or uninsulated). The matrix of the experiment is given in table. 3.4.

The type of wire has no effect on the geometric parameters of the experimental model.

In the table 3.4 the following designations are accepted:

"-" - minimum value:

- 10 kA for lightning current;

- 6 kV for line voltage;

- non-insulated wire.

"+" - maximum value:

- 20 kA for lightning current;

- 35 kV for line voltage;

- protected wire.

Table 3.4 - Matrix of the experiment for the study of the capture zone of a direct lightning strike

	I_l	U	Wire type
1	-	-	-
2	-	+	-
3	+	-	-
4	+	+	-
5	-	-	+
6	-	+	+
7	+	-	+
8	+	+	+

For the experiments, the initial parameters were chosen that correspond to the basic principles of modeling and do not complicate the experiments.

Based on the material presented in Chapter 2 of the work using formula (2.44), we calculated the modeling coefficients to determine the geometric parameters of the model and determined that the similarity coefficient for currents of 10 kA is equal to 43, and for 20 kA – 68.

In this way, the model height of the wire suspension was calculated, it will be equal to the following values:

$$\begin{aligned} h_1 = h_5 = 0,2 \text{ m}; & \quad h_2 = h_6 = 0,35 \text{ m}; \\ h_3 = h_7 = 0,13 \text{ m}; & \quad h_4 = h_8 = 0,22 \text{ m}. \end{aligned}$$

Results of experimental studies

When conducting a series of experiments, a 2.4 MV PUG was used as a voltage source. 8 series of experiments were conducted, 300 experiments in each series. The number of experiments in the series was determined by the probability determination error and was determined by the formula

$$\Delta b = \pm t S_{\{b\}}$$

For ease of presentation, the obtained results are entered in the table. 3.4

Table 3.4 - Model results of experimental studies

The height of the wire suspension, H_{sus} , m	The distance from which the wire receives direct lightning strikes, X, m	
	SIP 3 1*50-20	AS – 50/8
0,2	0,25	0,37
0,35	0,425	0,62
0,13	0,17	0,245
0,22	0,27	0,4

The results of the experiments showed that for lines with shielded wires, the capture zone is one and a half times smaller than the capture zone of an uninsulated wire. The capture zone is understood as the area on one side of the PL from which it collects direct lightning strikes. The size of this zone is usually determined by regulatory documents. Current standards determine the dependence of the width of the capture zone on the height of the overhead line. An example of such a width at the same height of the PL is shown in Fig. 3.9 [82].

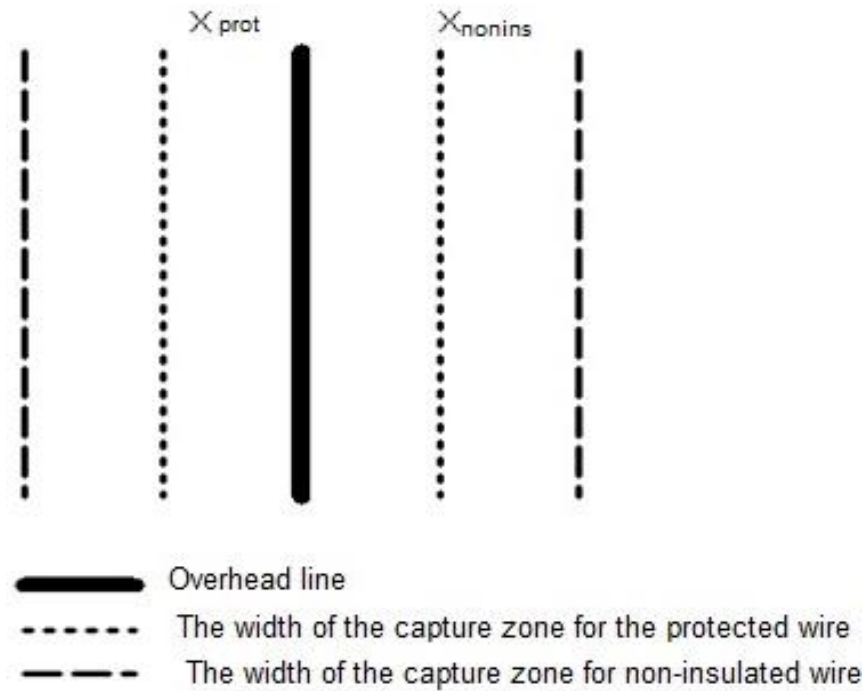


Figure 3.9 - Experimental values of the width of the lightning arrest zone for different types of wires

As can be seen from the obtained results, for an uninsulated wire, the capture zone is not $3 \cdot H_{sus}$, but $2 \cdot H_{sus}$, which indicates that lines of medium voltage classes are affected by direct lightning strikes less than once a year, compared to the number of such injuries obtained on the basis of methods calculation according to regulatory documents. Such a difference can significantly affect the lightning resistance indicators of similar lines, which determines the possibility of changing approaches to lightning protection of lines of medium voltage classes.

As can be seen from the table. 3.4, the capture zone of the SIP wire - 3 1 * 50-20 is almost 2 times smaller than the capture zone of an uninsulated wire and does not exceed the height of the line suspension by much, so it can be said that the capture zone of the protected wire is equal to H_{sus} . This fact shows that N_{dsl} for PPL is much smaller than for PL.

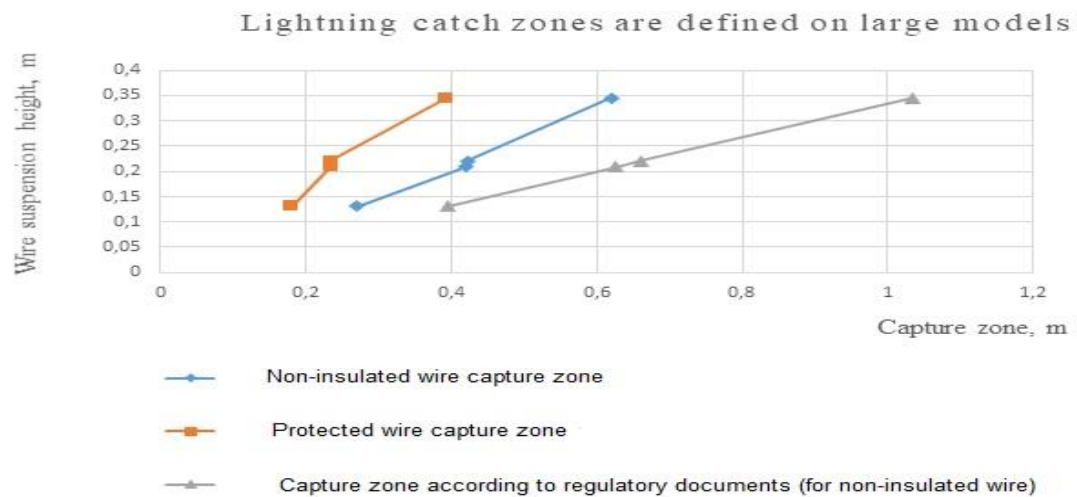


Figure 3.9 - Experimental values of lightning arrest for different types of wires in comparison with the normative value

The values of the width of the lightning arrest zone obtained as a result of experimental studies and calculated according to the methodology of regulatory documents (for non-insulated wire) are shown in Fig. 3.9. From fig. 3.9 clearly shows that the values of the width of the capture zone obtained during calculations significantly exceed similar data obtained experimentally. This fact makes it possible to state that the lines of medium voltage classes have a much smaller number of direct lightning strikes to the wires than is determined by the calculation method. Thus, at the design stage, experimentally obtained values of the width of the capture zones should be taken into account, which will lead to a reduction in the estimated number of direct lightning strikes.

CHAPTER 4. DEVELOPMENT OF THE MATHEMATICAL MODEL OF THE EXPERIMENT

Regression analysis of the obtained results

Each experiment contains an element of uncertainty due to insufficient accuracy, which is caused by the conditions of conducting the experiment, the inability to take into account all factors, and conducting an insufficient number of experiments. Setting up repeated (or parallel) experiments does not give completely identical results, because there is always experimental error (reproducibility error) [84]. This error should be evaluated by parallel experiments. To do this, the experiment is repeated as many times as possible under the same conditions, and then the arithmetic average of all results is taken:

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i \quad (4.1)$$

The deviation of the result of any experiment from the arithmetic mean can be expressed as the difference $y_i - \bar{y}$, where y_i is the result of a separate experiment. The presence of a deviation indicates the variability of the variation of the values of repeated experiments. The variance is most often used to measure this variability

$$\delta^2 = \frac{1}{n-1} \sum_{i=1}^n (y_i - \bar{y})^2 \quad (4.2)$$

where $(n - 1)$ is the number of degrees of freedom, equal to the number of experiments minus one. One degree of freedom is used to calculate the mean.

The variance of the entire experiment is obtained by averaging the variances of all experiments. According to the terminology adopted in the planning of the experiment, we are talking about the calculation of the dispersion of the optimization

parameter (feedback) δ_y^2 or, what is the same, the dispersion of the reproducibility of the experiment δ_{repr}^2 [85].

When calculating the dispersion of the optimization parameter, the square of the difference between the value of y_j in each experiment and the average value of n repeated observations of y must be summed over the number of experiments in the matrix N , and then divided by $N(n-1)$:

$$\delta_y^2 = \frac{\sum_{i=1}^N \sum_{j=1}^n (y_{ij} - \bar{y}_i)^2}{N(n-1)}, \quad (4.3)$$

where $i = 1, 2, \dots, N$; $j = 1, 2, \dots, n$.

Such a formula can be used in cases where the number of repeated experiments is the same in the entire matrix.

The reproducibility variance is easiest to calculate when the equality of the number of repeated experiments is observed at all experimental points. In practice, quite often we have to face cases when the number of repeated experiments is different. This happens due to rejection of rough observations, uncertainty of the experimenter in the correctness of some results (in such cases there is a desire to repeat the experiment again and again), etc. [85 - 87].

Then, when averaging the variances, you have to use the weighted average value of the variances, taken taking into account the number of degrees of freedom:

$$\delta_y^2 = \frac{\sum_{i=1}^N \delta_i^2 v_i}{\sum_{i=1}^N v_i}, \quad (4.4)$$

where δ_i^2 is the variance of the i th experiment; v_i is the number of degrees of freedom in the i th experiment, which is equal to the number of parallel experiments n_i minus 1.

The number of degrees of freedom of the average variance is taken to be equal to the sum of the number of degrees of freedom of the variance from which it is calculated.

Verification of homogeneity of variances

The homogeneity of variances is checked using various statistical criteria. The simplest of them is Fisher's test, designed to compare two variances. Fisher's criterion (F -criterion) is the ratio of a larger variance to a smaller one. The obtained value is compared with the table value of the F -criterion [85, 88].

If the compared number of variances is more than two and one variance significantly exceeds the others, you can use the Cochran test. This criterion is suitable for cases where all points have the same number of repeated experiments. At the same time, the variance is calculated in each horizontal row of the matrix:

$$\delta^2 = \frac{1}{n-1} \sum_{j=1}^n (y_j - \bar{y})^2, \quad (4.5)$$

and then, of all the variances, there is the largest $\delta_{\mathbf{max}}^2$, which is divided by the sum of all the variances. Cochran's criterion is the ratio of the maximum variance to the sum of all variances.

$$G = \frac{\delta_{\mathbf{max}}^2}{\sum_{i=1}^N \delta_i^2}. \quad (4.6)$$

The hypothesis of homogeneity of variances is confirmed if the experimental value of the Cochran criterion does not exceed the tabulated value. Then you can average the variances and use formula (4.3).

In our case, the Cochran criterion is 0.35, while the table value is 0.28. Thus, the hypothesis about homogeneity of variances is confirmed, since the experimental value of the Cochran criterion does not exceed the tabular value.

Determining the coefficients of the regression equation

For any number of factors, the coefficients of the regression equation will be calculated according to the formula

$$b_j = \frac{\sum_{i=1}^N x_{ji} y_i}{N}, \quad j = 0, \dots, k. \quad (4.7)$$

There are no differences when calculating nonlinear models based on fractional replicas. Additional difficulties arise if the coefficients of the incomplete quadratic equation are determined (if we want to take into account interaction effects). The regression equation has the form [85, 89].

$$y = b_0 + b_1 x_1 + b_2 x_2 + \dots + b_k x_k + b_{12} x_1 x_2 + b_{13} x_1 x_3 + \dots + b_{k-1,k} x_{k-1} x_k.$$

where, y is the response value predicted by this equation,

$x_1, x_2, \dots, x_k$ are factors affecting the process.

In a full factorial experiment, all interaction coefficients can be estimated according to the methodology given in Chapter 2 of the work.

The formula for calculating the coefficients can be drawn as follows:

$$b_{uj} = \frac{\sum_{i=1}^N y_i x_{ui} x_{ji}}{N}, \quad (4.8)$$

where $u, j=1, 2, \dots, k$ is the measure of factors, $u \neq j$.

As a result of calculating the coefficients based on the obtained experimental data, the regression equation will have the following form:

$$y = 0,31484 + 0,07727x_1 - 0,06739x_2 - 0,06055x_3 - 0,02027_1 x_2 + \\ + 0,01552 x_1 x_3 - 0,01200 x_2 x_3 - 0,00170 x_1 x_2 x_3$$

where, y is the probability of damage to the line by a direct lightning strike,

x_1 is the height of the wire suspension,

x_2 – wire type,

x_3 is the distance from the axis of lightning to the wire.

Checking the adequacy of the model

The residual sum of squares is quite suitable for characterizing the average spread with respect to the regression line. The inconvenience is that it depends on the number of coefficients in the equation. Enter as many coefficients as you have performed independent experiments, and you will get a residual sum equal to zero. Therefore, they prefer to attribute it to one "free" experience. The number of such experiments is called the number of degrees of freedom ν .

The residual sum of squares divided by the number of degrees of freedom is called the residual variance, or adequacy variance δ_{ad}^2 :

$$\delta_{ad}^2 = \frac{\sum_{i=1}^N (y_i - \hat{y}_i)^2}{\nu} \quad (4.9)$$

To test the hypothesis about the adequacy of the model, the F -criterion is used, which is defined as:

$$F = \frac{\delta_{ad}^2}{\delta_y^2} \quad (4.10)$$

where δ_y^2 is the reproducibility variance with its number of degrees of freedom

If the calculated value of the F -criterion does not exceed the table value, then, with the corresponding confidence probability, the model can be considered adequate. If the table value is exceeded, this pleasant hypothesis has to be rejected.

This method of calculating the variance of adequacy is suitable if the experiments in the planning matrix are not duplicated, and information about the dispersion of reproducibility is extracted from parallel experiments at the zero point or from previous experiments [85].

Two cases are important: 1) experiments at all points of the plan are duplicated the same number of times (uniform duplication); 2) the number of parallel experiments is not the same (uneven duplication).

In the first case, the adequacy variance must be multiplied by n , where n is the number of repeated experiments:

$$\delta_{ad}^2 = \frac{\sum_{i=1}^N (y_i - \widehat{y}_i)^2}{\nu}$$

Such a modification of the formula is quite natural. The greater the number of parallel experiments, the more likely average values are estimated. Therefore, the requirements for differences between experimental and calculated values become stricter, which is reflected in an increase in the F -criterion.

In the second case, when one has to deal with uneven duplication, the situation becomes more complicated. Even when the experimenter plans to conduct an equal number of parallel experiments, it is often not possible to implement all of them for one reason or another. In addition, sometimes it is necessary to reject individual experiments as falling out of observation.

In the case of uneven duplication, the orthogonality of the planning matrix is violated and, as a result, the calculation formulas for the regression coefficients and their errors, as well as for the adequacy variance, are changed [85].

The general formula can be written for the dispersion of adequacy:

$$\delta_{ad}^2 = \frac{\sum_{i=1}^N n_i (y_i - \widehat{y}_i)^2}{\nu} \quad (4.12)$$

where, N is the number of different experiments (the number of rows of the matrix);

n_i is the number of parallel experiments in the i th row of the matrix;

$\bar{y}_i$ – arithmetic mean of n_i parallel experiments;

$\hat{y}_i$ is the value predicted by the equation in the i th experiment.

The meaning of this formula is very simple: the greater the number of repeated experiments, the more weight is given to the difference between the experimental and calculated value.

A universal calculation formula can be written for b-coefficients. It all depends on what the plan was and how the experiments were duplicated. Every time you have to make special calculations using the method of least squares.

According to (4.10) and (4.12), the calculated value of the F -criterion is 0.15819, while the tabulated value is 5.96. Thus, we can conclude that the model can be considered adequate.

Checking the significance of the coefficients

The significance test of each coefficient is carried out independently. It can be carried out in two equivalent ways: by checking the Student's t test or by constructing a confidence interval. When using a full factorial experiment or regular fractional replicates, the confidence intervals for all coefficients (including interaction effects) are equal to each other [90].

First of all, we need to find the variance of the regression coefficient $\delta_{b_j}^2$. It is determined by the formula:

$$\delta_{b_j}^2 = \frac{\delta_y^2}{N}; \quad (4.13)$$

It can be seen from this formula that the variances of all coefficients are equal to each other, because they depend only on the error of the experiment and the number of experiments.

Now it is easy to construct a confidence interval:

$$\Delta b_j = \pm t \delta_{b_j}, \quad (4.14)$$

where t is the tabular value of the Student's criterion with the number of degrees of freedom with which was determined δ_y^2 and the chosen level of significance (usually 0.05); δ_{b_j} is the squared error of the regression coefficient.

The formula for the confidence interval can be represented as:

$$\Delta b_j = \pm \frac{t \delta_y}{\sqrt{N}}; \quad (4.15)$$

The coefficient is significant if its absolute value is greater than the confidence interval. The confidence interval is given by the upper and lower bounds of $b_j + \Delta b_j$ and $b_j - \Delta b_j$ [90].

The higher the confidence interval (at a given level of significance α), the more confidently we can talk about the significance of the coefficient. If the absolute value of the coefficient is greater than the confidence interval, then the coefficient is significant.

The second method of checking the significance of the coefficients is carried out according to the Student's criterion:

$$t = \frac{|b_j|}{\delta_{b_j}}. \quad (4.16)$$

The calculation of the value of the t -criterion is compared with the tabular value at a given level of significance α and the corresponding number of degrees of freedom. If the calculated value of the t -criterion exceeds the table value, then the hypothesis about the significance of the coefficient is not rejected. Otherwise, the coefficient is considered insignificant and excluded from the regression equation.

Thus, after checking the significance of the coefficients, the regression equation has the following form:

$$y = 0,31484 + 0,07727x_1 - 0,06739x_2 - 0,06055x_3$$

Writing the obtained regression equation in real units, the equation will look like this:

$$P_{DSL} = 0,31484 + 0,07727 * H_{sus} - 0,06739 * K - 0,06055 * X$$

The obtained expression allows you to calculate the probability of damage to PL and PPL by a direct lightning strike with different designs of lightning lines and properties. The use of such an expression will make it possible to clarify the method of determining the lightning resistance of PPL and PL at the design stage.

Analysis of results using Mamadani's fuzzy inference method

Fuzzy Logic Toolbox is a package of application programs included in the MatLab environment. It allows creating systems of fuzzy logic derivation and fuzzy classification within the MatLab environment with the possibility of their integration in Simulink [91 - 96].

Main properties:

- definition of variables, vague rules and functions of belonging;
- interactive viewing of fuzzy logic output;
- modern methods: adaptive fuzzy inference using neural networks, fuzzy clustering;
- interactive dynamic modeling in Simulink;
- generation of portable C code using Real-Time Workshop.

The Fuzzy Logic package contains five graphical editors for presenting the necessary information in the process of designing, creating and testing fuzzy models.

The Fuzzy Logic package contains modern methods of fuzzy modeling, including [92]:

- adaptive fuzzy inference using neural networks for automatic formation of the membership function in the process of training them on input data;
- fuzzy logic and clustering for pattern recognition tasks;
- the possibility of choosing the well-known Mamdani method or the Sugeno method for creating hybrid fuzzy systems.

The package allows work:

- in the graphical interface mode;
- in command line mode;
- using blocks and examples of the Simulink package.

The basic concept of the Fuzzy Logic Toolbox is the FIS-structure - a fuzzy inference system (Fuzzy Inference System). The FIS-structure contains all the necessary data for the implementation of the functional mapping "inputs-outputs" on the basis of fuzzy logical derivation according to the scheme shown in Fig. 4.1 [93].

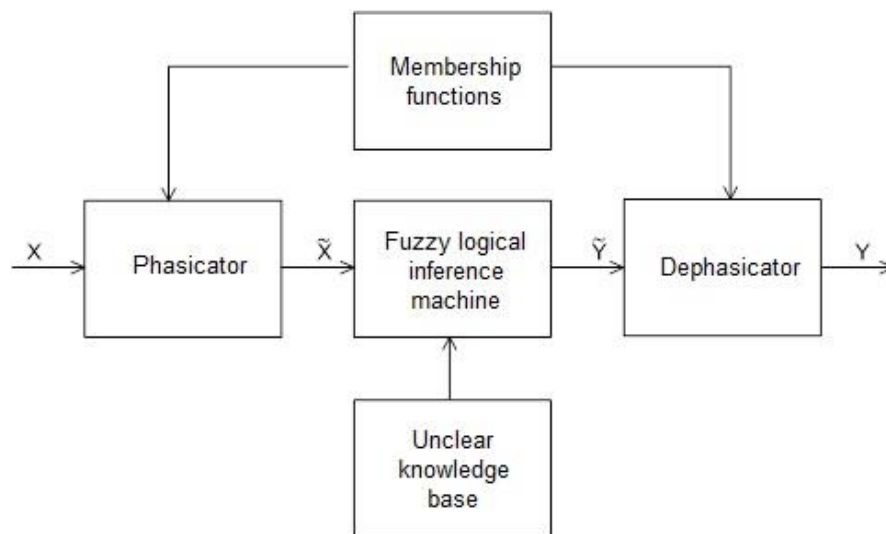


Figure 4.1 – Fuzzy logic inference

Notation: X – input distinct vector; $\tilde{X}$ – the vector of fuzzy sets corresponding to the input vector X ; $\tilde{Y}$ – the result of logical derivation in the form of a vector of fuzzy sets; Y is the original clear vector.

Composition of the graphic interface

The command (function) `fuzzy` from the command line mode starts the main interface program of the Fuzzy Logic package - the fuzzy output system editor. The main window is shown in fig. 4.2 [94].

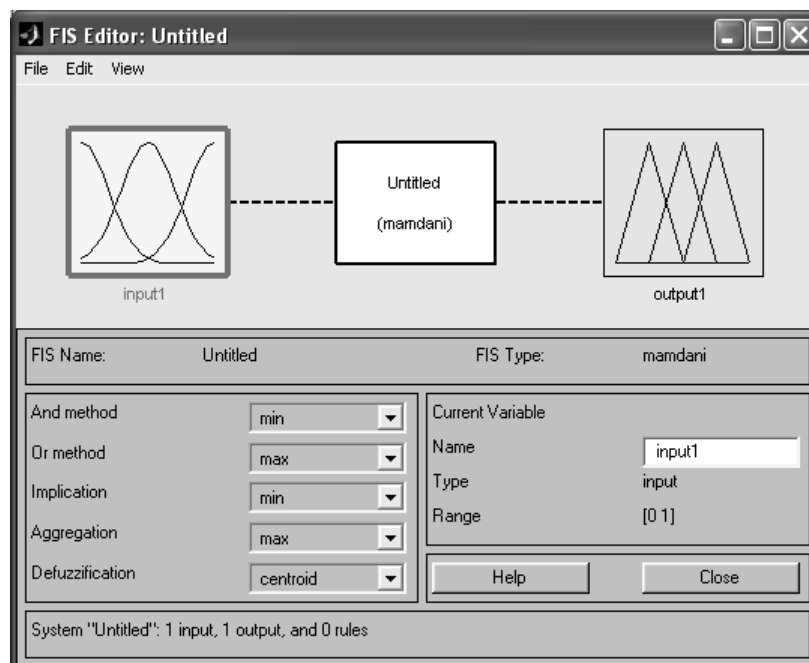
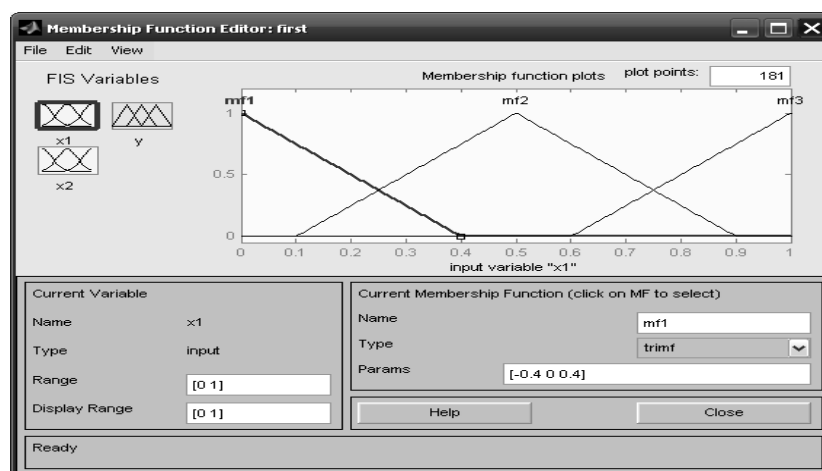


Figure 4.2 – View of the FIS Editor window

To go to the membership function editor, you need to double-click on any of the functions, where you can select the properties of a specific one, the window is shown in fig. 4.3.



Drawing. 4.3 – Membership function editor

The following properties of the function are indicated at the bottom of the window:

Current Variable:

- Name – name of the function;
- Type – type (input or output);
- Range – variable range;
- Display Range – displayed range.

Current Membership Function:

- Name – the name of the current membership function;
- Type – the type of membership function term – selected from the list (triangular, trapezoidal, 1st and 2nd order Gaussian and others);
- Params – numerical values of the membership function term.

To call the editor, you need to select the Rules... command in the Edit menu, the main window shown in fig. 4.4 [93].

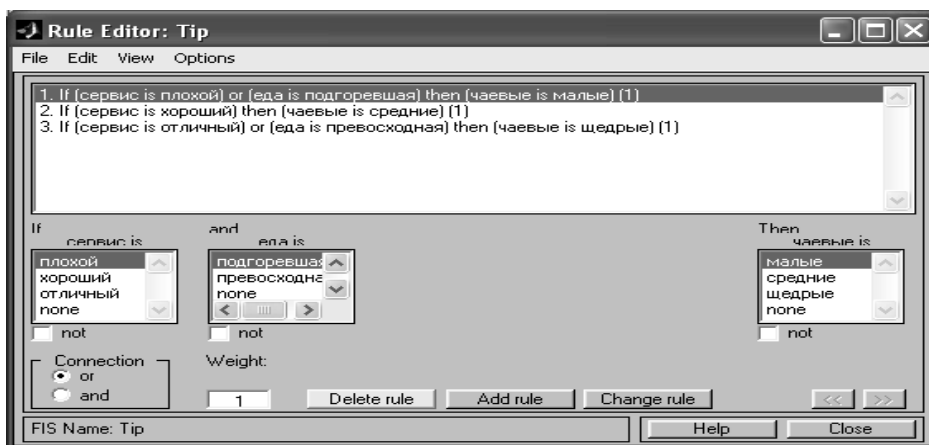


Figure 4.4 – Rules editor

You can view the input-output surface corresponding to the synthesized fuzzy system (Fig. 4.5). To display this window, use the View surface... command of the View menu [96].

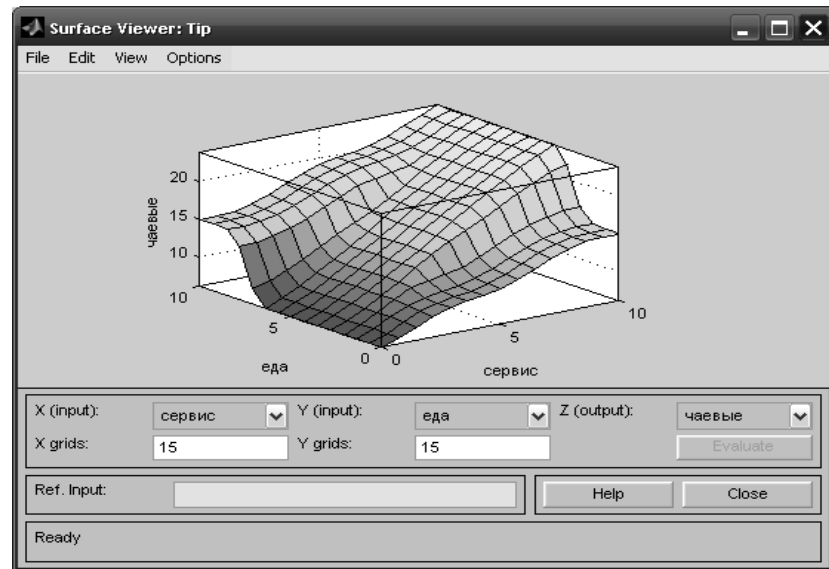


Figure 4.5 – Response surface of a fuzzy system

Using the experimental data obtained in section 3, we will construct the response surfaces of the fuzzy system for 6 or 35 kV lines, with non-insulated or shielded wire.

We will get 4 response surfaces, where the wire type and wire voltage class will be specified, and the lightning current and capture zone will vary. Figures 4.6 - 4.9 show the change in the probability of a direct lightning strike in PL and PPL.

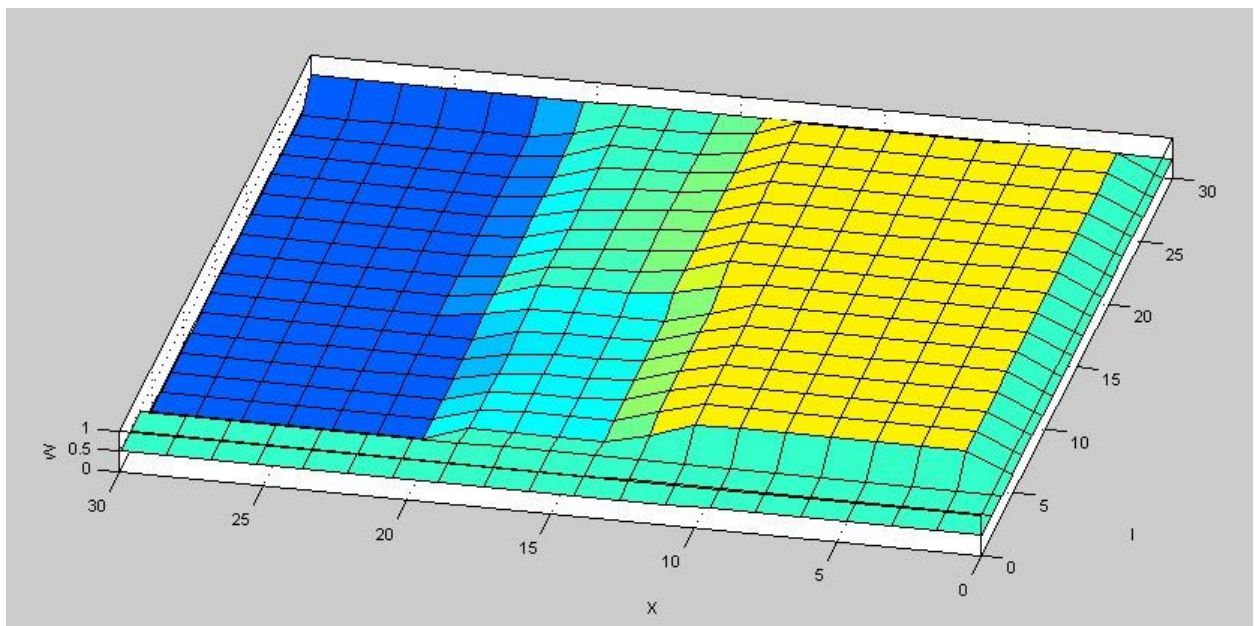


Figure 4.6 – Surface obtained for a 6kV line with non-insulated wires

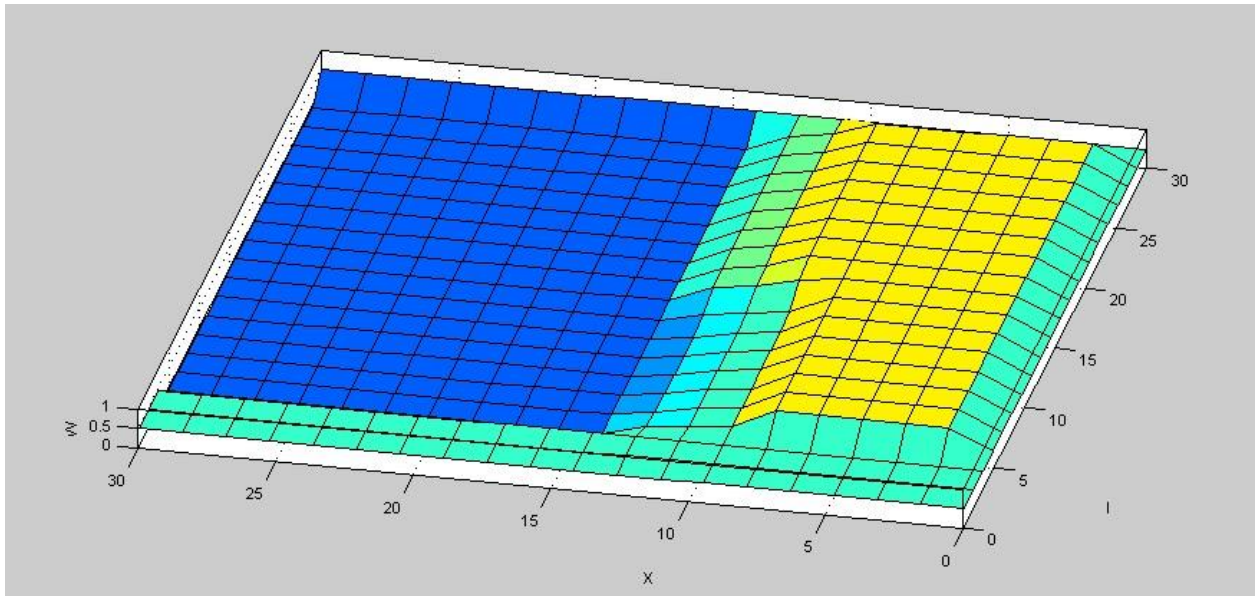


Figure 4.7 – Surface obtained for a 6 kV line with shielded wires

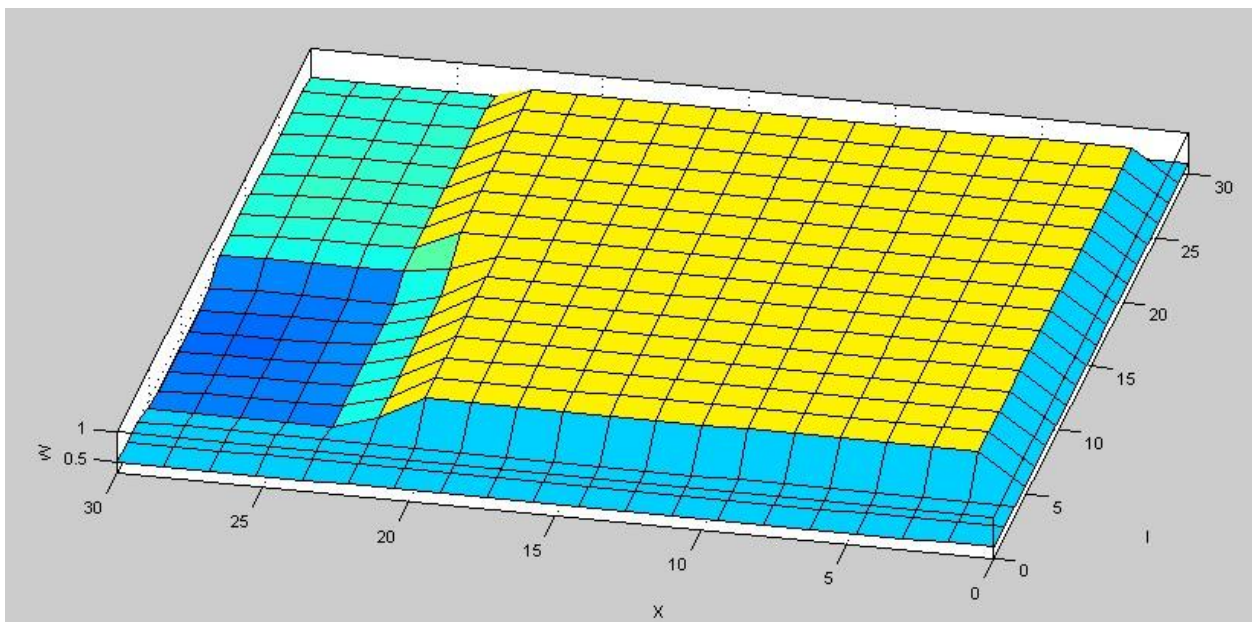


Figure 4.8 – Surface obtained for a 35kV line with non-insulated wires

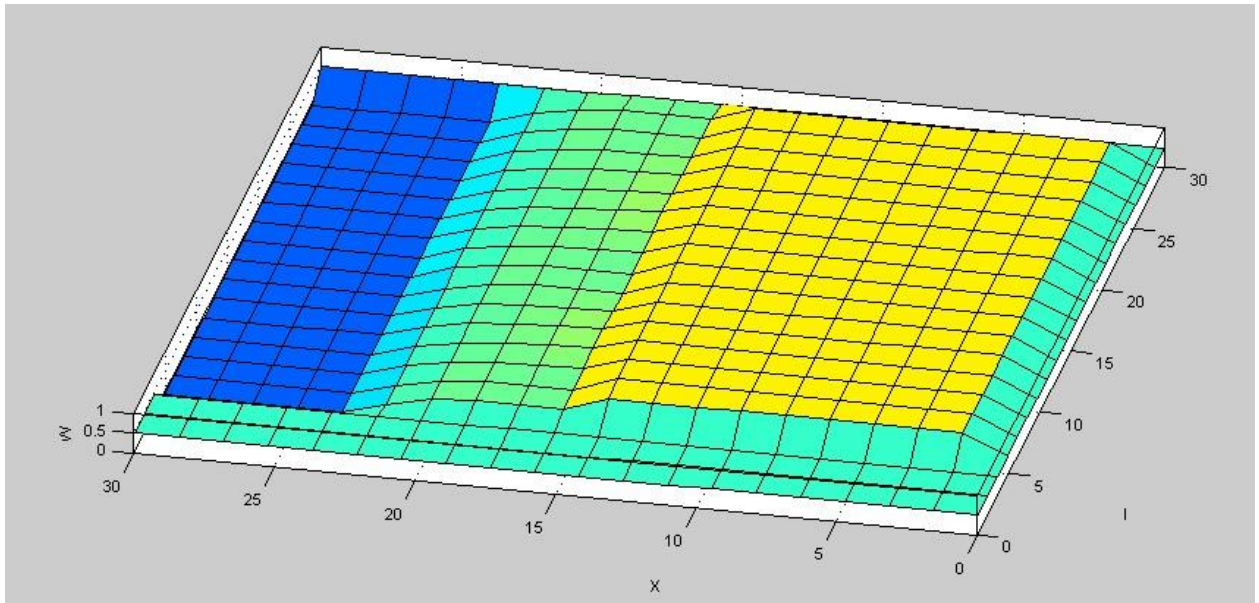


Figure 4.9 – Surface obtained for a 35 kV line with shielded wires

As can be seen from the obtained results, modeling with the help of fuzzy logic made it possible to take into account the variational component of the lightning current, which made it possible to construct the response surfaces of the fuzzy system and to see the probability of PL damage, taking into account the type of wire and the voltage class of the power transmission line.

Methodology for calculating the number of direct lightning strikes on overhead power lines.

The intensity of thunderstorm activity is most objectively estimated by the number of lightning strikes per 1 km² of the earth's surface n^* in 1 thunderstorm season. To estimate this value, it is necessary to know the number of thunderstorm hours T_h or days T_d for the area where the substation or substation is located [81, 97, 98].

In rough estimations, it is assumed that $n^* = 0.06 \div 0.1$ lightning strikes per 1 km² of the earth's surface occur on average in 1 thunderstorm hour. Therefore, the average number of impacts per 1 km² during the year can be estimated by the formula [81]:

$$n = n^* \cdot T_h = 1,5 \cdot n^* \cdot T_d. \quad (4.16)$$

The distribution of thunderstorms on the earth's surface is uneven. Therefore, the indicator of thunderstorm activity is usually given in the form of special maps. However, in general, the analysis shows that in the equatorial regions there are zones where up to 220 thunderstorm days per year are observed. In the countries of the temperate zone - usually 20 - 50 thunderstorm days or 30 - 120 thunderstorm hours. Thunderstorms are a rare event in the polar regions. In mountainous conditions and for objects of great height, as well as in heterogeneous soils, it is necessary, in addition, to reckon with an increase in the probability of lightning with ascending leaders, as well as with the selective vulnerability of certain areas of the earth's surface.

The number of direct lightning strikes to ground objects can be estimated by the formula [81]:

$$N_{\text{dls}} = n \cdot S_c, \quad (4.17)$$

where, S_c is the calculated area of the earth's surface from which lightning strikes are "charged" to the object, km^2 .

For a single concentrated object with a height h , the average annual number of direct lightning strikes can be calculated as follows [81]:

$$N_{\text{dls}} = \pi \cdot n \cdot R_{\text{eq}}^2, \quad (4.18)$$

where $R_{\text{eq}} = (3 \dots 5) h$ is the equivalent radius of the area from which the discharges are charged to the object.

This formula roughly describes the observed dependence of the number of object lightning strikes on its height at $h \leq 150$ m. At high altitudes, the growth of the number of object strikes by negative downward lightning slows down, but the number of lightning strikes with ascending leaders, which have other characteristics, increases rapidly.

For open distribution devices of high-voltage substations 3-500 kV, the number of direct lightning strikes is calculated according to the formula [99]:

$$N_{\text{dls}} = n \cdot S_c = n (l+7h) \cdot (b+7h) \cdot 10^{-6}, \quad (4.19)$$

where h is the height of lightning conductors;

l and b - the length and width of the substation territory, m.

The number of direct lightning strikes per year for long objects (power lines) is usually estimated using the specific number of direct lightning strikes per 100 km of length and per 100 thunderstorm hours N_{dls}^* .

At support heights $h \leq 30$ m, N_{dls}^* is determined by the formula [81]:

$$N_{\text{dls}}^* = (4 \div 6) h_{\text{av}}; \quad (4.20)$$

$$h_{\text{av}} = h_{\text{sus}} - 2/3 f \quad (4.21)$$

where, h_{sus} - the height of suspensions of cables or upper wires on the support, m;

f - sag arrow, m.

At support heights $h > 30$ m, the formula [81] is more acceptable for calculating N_{dls}^* :

$$N_{\text{dls}}^* = 5h_{\text{av}} + \frac{(h_{\text{av}}^2 + b)}{30} \quad (4.22)$$

where b is the distance between cables or upper phase wires (in the absence of cables), m.

As can be seen from both formulas for calculating N_{dls}^* , a lightning strike on a PL can be considered a rare phenomenon. For example, a 35 kV two-circuit line with $h_{\text{av}} = 19.3$ m and $b = 0$ m (one cable) at $t_h = 30$ h per year experiences an average of 35

lightning strikes for every 100 km of length. Without lightning protection, such a line will not be able to work normally.

The suspension of lightning protection cables, which is the main lightning protection measure on lines of voltage classes 110 kV and above, is not very effective for lines 6 - 35 kV, which is caused by the low impulse strength of the insulation of 6 - 35 kV. As a result, the probability of reverse overlaps in the event of lightning strikes in the support or in the cable would turn out to be quite significant at normal values of the resistance of the grounding of the supports. Therefore, lines of 6 - 35 kV are built, as a rule, without cables. Exceptions are only particularly responsible 35 kV lines on metal supports [100, 101].

Despite the absence of cables, 6 - 35 kV lines have a number of features that create more favorable conditions for their lightning protection. First, these lines are less susceptible to direct lightning strikes due to their relatively small height and length. Often they are partially protected from direct lightning strikes by objects located near the line: buildings, tall trees, lines of higher voltage, etc.

Secondly, the presence of an isolated or grounded neutral through an arc extinguishing reactor in networks of 6 - 35 kV facilitates the fight against the consequences of impulse overlaps of the insulation, contributes to the extinguishing of the arc of a single-phase short circuit to the ground. It can be assumed that cases of lightning overlaps of the insulation of only one of the phases of the line do not cause its disconnection. The resulting arc of a single-phase overlap is extinguished, and the danger for 6 - 35 kV lines is represented only by overlaps between phases or simultaneous overlaps from several phases to the ground. With interphase overlaps, the probability of arc extinction remains high, because the operating voltage gradient along the overlap path on these lines is small.

Thirdly, 6 - 35 kV lines are often built on wooden supports. In this case, the length of the path of the lightning overlap of the insulation increases due to the impulse strength of the tree of the traverse and the support rack. The probability of overlap and the probability of transition of pulse overlap into a short-circuit arc decreases.

However, these advantages of wooden supports cannot be fully realized due to the possibility of splitting wooden parts during direct lightning strikes. In order to combat splitting of the traverses and struts of the supports, in some cases it is necessary to shunt the wooden parts of the supports with current-dissipating metal descents [101].

Unlike lines of a higher voltage class, lines of 6 - 35 kV on metal supports are often disconnected due to the effect of induced overvoltages, which can cause the overlap of the 35 kV insulation, five times more than the number of overvoltages dangerous for the 110 kV network. The reason for this is also the low impulse strength of the insulation of 6-35 kV lines on metal supports [99].

For 6-35 kV lines, the total number of lightning shutdowns per year is:

$$n_{\Sigma} = n_{\text{dls}} + n_{\text{ind}}, \quad (4.23)$$

where n_{dls} and n_{ind} are the specific (per 100 km and 100 hours of thunderstorms) number of lightning shutdowns due to direct lightning strikes and due to induced overvoltages, respectively [101].

These values are determined by the formulas:

$$n_{\text{dls}} = N_{\text{dls}}^* [P_{p3} P_{a\Sigma} + (P_{p2} - P_{p3}) P_a] (1 - P_{\text{AR}}), \quad (4.24)$$

$$n_{\text{ind}} = [N_{\text{ind}3} P_{a\Sigma} + (N_{\text{ind}2} - N_{\text{ind}3}) P_a] (1 - P_{\text{AR}}), \quad (4.25)$$

where, P_{p2} and P_{p3} are the probability of two-phase and three-phase over-recovery of the PL insulation,

P_a is the probability of arc occurrence,

P_{AR} is the probability of an AVR tripping,

$N_{\text{ind}2}$ and $N_{\text{ind}3}$ - specific number of two-phase and three-phase overlaps of PL insulation.

The method of calculating direct lightning strikes in the power line, taking into account the type of wire.

To estimate the average number of insulation overlaps on overhead lines of medium voltage classes per year, it is necessary to take into account direct lightning strikes and induced overvoltages. The estimate of the number of direct lightning strikes in the power line, each of which will lead to insulation overlap, for lines 6 - 35 kV will be 100%. For induced overvoltages, it is necessary to select all lightning strikes that can occur at a distance greater than the capture zone of a given transmission line, selecting from them those strikes that will lead to overvoltages that exceed the overlap voltage of the insulation of the transmission line.

According to regulatory documents, the number of direct lightning strikes to overhead lines with uninsulated and protected wires is calculated in the same way, according to the formula [102]:

$$N_{dls} = 0,067 * n * 6 * H_{sus} * L, \quad (4.26)$$

where n is the number of thunderstorm hours per year;

L - line length, km;

H_{sus} - height of suspension of wires, m.

As we can see, this formula uses the expression $(6 * H_{sus})$, which means that the capture occurs on both sides of the line, with the capture zone in $3 H_{sus}$. In this case, the voltage class of the line is not taken into account. However, in the literature [81] there are graphs from which it can be seen that the capture zone is from $2 H_{sus}$ to $5 H_{sus}$ for PL with non-insulated wires, depending on the height of the supports, that is, the voltage class of the PL.

According to the results of the experiments, the number of direct lightning strikes depends significantly on the value of the lightning capture zone.

According to experimental data obtained on large-sized models, the capture zone for non-insulated and shielded wires is significantly different. Accordingly, the number of direct lightning strikes in the PL will also differ.

For calculations, let's assume that the number of thunderstorm hours per year is equal to 100 hours, consider a line 100 km long. The voltage class of the line will be 35 kV. Let the lightning current be equal to 20 kA.

Let's consider the number of direct hits in the PL according to the methodology given in regulatory documents and according to the values obtained experimentally for non-insulated and protected wires.

For the 35 kV line, typical supports PS 35P-5M are used, the height of suspension of wires on these supports is 15 m.

According to the calculation method [102] and according to (4.26), the number of direct lightning strikes in the PL will be equal to:

$$N_{dls} = 0,067 * n * 6 * H_{sus} * L = 0,067 * 6 * 15 = 6,03$$

However, if instead of $6 * H_{sus}$ we use the values obtained from experimental studies, then the number of direct lightning strikes in a line with non-insulated wires will be:

$$N_{dls} = 0,067 * 2 * 28,73 = 3,85$$

For a line with protected wires, the number of direct lightning strikes will be:

$$N_{dls} = 0,067 * 2 * 15,96 = 2,14$$

As can be seen from the calculation, depending on how to calculate the lightning damage of the line, we will get different values [103].

Historically, it has happened that due attention was not paid to the issue of lightning protection of PLs of medium voltage classes, the existing methods do not correspond to reality. They do not take into account a significant factor, the type of wire, which is of significant importance when calculating the lightning susceptibility of the line.

CHAPTER 5. MODERN AND PROSPECTIVE MEANS OF PROTECTION AGAINST OVERVOLTAGE

Classification of surge protection measures

Measures and means of protection against overvoltages are divided into organizational and technical. Organizational measures of protection, in turn, include system and optimization, technical measures and means of protection - preventive and switching [104, 105].

System measures are not special surge protection measures. However, the construction of parallel lines and the expansion of equipment reserves, the installation of synchronous compensators and shunting reactors and other measures make it possible to prevent or significantly reduce the probability of developing a system accident, which leads to the greatest losses. These measures also limit the increase of the operating voltage above the permissible level.

Optimization measures are also not special surge protection measures in the narrow sense of the word. As the name implies, they involve the development and selection at the design stage, as well as the implementation in operating conditions of the optimal strategy for operating the network, switching and eliminating the negative effects of overvoltages. Among them should be included the recloser, selective relay protection of the network, automatic regulation of the excitation of generators and synchronous compensators, timely and thorough prevention of isolation and repair of equipment.

Preventive protection measures have a permanent impact on the network. Their purpose is to prevent the occurrence of overvoltages or to help limit their magnitude. The beneficial effect of preventive protection measures is manifested throughout the transition process. Such measures include, in particular, the use of switches whose operation does not cause the appearance of large overvoltages (for example, switches without dangerous re-ignition of the arc between contacts and with shunting supports),

lightning protection cables, grounding of supports on lines, capacitive protection of insulation of transformer windings, grounding neutrals of transformers through arc extinguishing reactors [104].

Switching means of protection against overvoltages, as a rule, contain switching elements, for example, spark gaps. They are triggered when the overvoltage at the point of their installation exceeds a certain critical value. This leads to a change in the scheme or network parameters. Overvoltage on the insulation is limited to permissible limits, and the probability of occurrence of overvoltages of high multiplicity is significantly reduced. Non-linear surge protectors can also be attributed to switching protection devices. In these devices there are no spark gaps and highly nonlinear resistors are permanently connected to the network. However, when the voltage on the ON-type diodes is increased above the maximum operating voltage, their resistance decreases sharply, which is equivalent to the triggering of spark gaps [104].

To protect equipment from direct lightning strikes, lightning conductors are used at substations and lightning protection cables on lines. Reducing the probability of dangerous lightning overvoltages during lightning strikes in lightning conductors and other grounded elements of lines and substations is achieved by connecting them to the ground while ensuring a sufficiently small grounding impulse resistance. Protection of insulation from waves running along the lines is carried out with the help of arresters and non-linear overvoltage limiters.

Protective gaps and tubular arresters

The simplest and cheapest surge protection device is a spark gap (SG).

In networks up to 35 kV, the SG s have a short length and can be shorted by birds sitting on the electrodes. In order to prevent short-circuits, additional gaps are created in the grounding descents of the SG.

In the table 5.1 shows the main characteristics of the 6 - 35 kV SG.

SG s have a number of disadvantages that limit their wide application. Their breakdown voltage has a large statistical spread, which greatly complicates the coordination of SG breakdown voltages with the characteristics of the protected insulation. Due to the sharp inhomogeneity of the electric field between the contacts, there is a significant increase in the discharge voltage of the SG when steep wave fronts affect overvoltage. In the region of a small pre-discharge time ($t_{sw} \leq 2 \mu s$), the volt-second characteristic of the insulation (taking into account the statistical spread) can pass below the volt-second characteristic of the SG (Fig. 5.1), i.e. at times $t \leq t_{sw}$, the insulation remains unprotected and can be damaged [104].

Table 5.1 - characteristics of SG

	Nominal voltage, kV				
	6	10	10	20	35
The length of the protective gap	20	40	60	140	250
Discharge voltage at 50 Hz, kV current	20	34	45	70	105
50% impulse voltage with positive polarity, kV	34	51	66	121	195
Also, with negative polarity, kV	34	53	68	134	220

Any tripping of the SG causes the formation of a short-circuit current arc, which cannot spontaneously extinguish in networks of 110 kV and above, and in some cases in networks of 35 kV and below. Each such short-circuit causes undesirable electrodynamic effects in the field of transformers and electric machines, accelerated wear and extraordinary revisions of circuit breakers, which allow a limited number of short-circuit current disconnections.

The tripping of SGs installed in parallel with the protected insulation causes a sharp cut in the voltage on it. This leads to the occurrence of dangerous gradient overvoltages on the longitudinal insulation (between turns and coils) of the windings of transformers, reactors and electric machines.

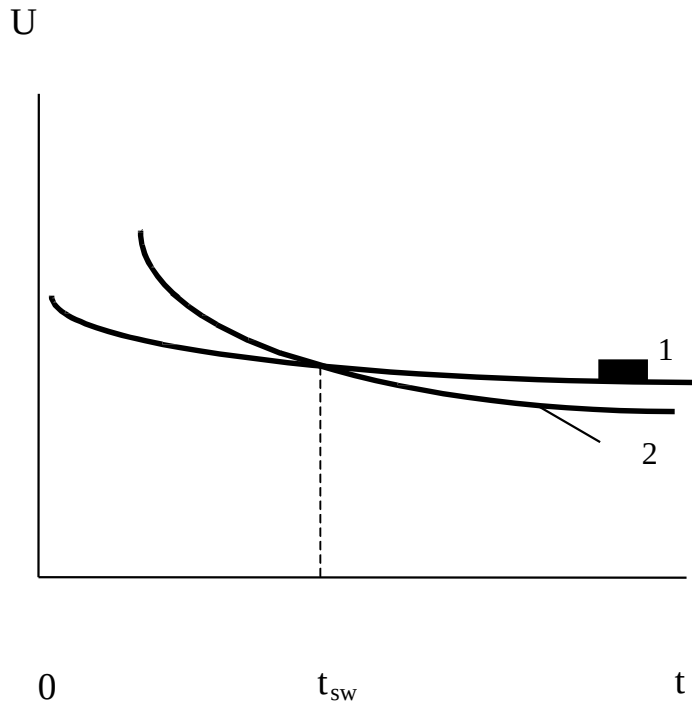


Figure 5.1 – volt-second characteristics of insulation (lower envelope – 1) and SG (upper envelope – 2)

Some improvement in performance can be obtained by forced arc quenching. For this purpose, in tubular arresters, the SG is placed in a tube made of a gas-generating material, for example, fiber or vinyl plastic. When a pulsed lightning current and a short-circuit current flow through the SG, a powerful arc burns, which causes high temperature, gas release and high pressure (up to several tens of atmospheres). Gases, exiting through the open end of the tube, create a longitudinal blow, and at the first passage of the current through the zero, the arc is extinguished [104].

Tubular arresters are devoid of one of the main disadvantages of protective SGs - the formation of a long short circuit, which is turned off by mains switches. However, tubular arresters also have other disadvantages of SG. They, as well as the presence of an exhaust zone, exclude the possibility of using arresters in the switchgear, as well as

near the switchgear transformer as the main device for protecting the electrical equipment of substations. However, they are still installed in a limited number at the approaches of lines to substations and at weakened points of lines.

Valve arresters

Until recently, the main means of protection against overvoltages was a valve arrester. This protective device consists of spark gaps and series non-linear resistors, sometimes called working resistors. In most valve arresters, shunt supports (SHS) are connected in parallel to the spark gaps. The latter serve to evenly distribute the voltage across the spark gaps.

When the valve arrester is affected by overvoltages exceeding its breakdown voltage, the SG breakdown occurs and the operating resistance is connected to the network. At the same time, the overvoltage at the installation point of the device is mainly determined by the voltage drop on the working resistances. It is sometimes called residual voltage on the arrester (U_{res}). This voltage should be $\sim 30\%$ less than the allowable voltage on the insulation being protected. The current flowing through the arrester after the impulse breakdown of the SG under the influence of a voltage of 50 Hz is called the accompanying current. This current is limited by the operating resistance of the device, the value of which increases sharply when the voltage on the arrester decreases. When the current passes through zero, the arc in the SG is extinguished, and the arrester returns to its initial state. Thus, SG valve arresters in the absence of overvoltages separate the working supports from the network and connect them at the moment of the appearance of overvoltages dangerous for isolation.

The spark gaps, if possible, should have a horizontal volt-second characteristic, that is, a small change in the breakdown voltage U_{bd} in a wide range of pre-discharge time (from μs to ms) and a small spread of U_{bd} . In addition, U_{bd} should not change after repeated passage of normalized impulse and accompanying currents, as well as during temperature fluctuations and exposure to shaking, shocks and vibration. SGs must

extinguish the arc of the accompanying current, as a rule, at the first crossing of it through zero [104].

To fulfill these requirements, SG of the following types are used:

- with a stationary arc of the accompanying current, which extinguishes practically in the same place where the breakdown occurs (used in arresters of the RVS, RVP and RVO series);

- with an arc rotating in the annular gap between the electrodes under the action of a magnetic field (such SGs are used in valve arresters of the RVM and RVMG series);

- with a stretching arc, which, moving between electrodes under the influence of a magnetic field, significantly (tens and hundreds of times) increases its length; arresters of the RVT and RVRD series are produced with such SGs.

The series resistance of the valve arrester should have a non-linear volt-ampere characteristic and the ability to repeatedly pass impulse and accompanying currents. Solid semiconductor materials are used for nonlinear resistors, the conductivity of which increases almost instantly when the applied voltage increases. Currently, NS are made of electrotechnical silicon carbide (carborund) SiC.

The specific resistance of carborundum grains is approximately 10^{-2} Ohm·m.

On their surface, there is a semiconducting barrier layer with a thickness of ~ 100 μm made of silicon oxide SiO₂.

The specific resistance of the barrier layer depends nonlinearly on the intensity of the electric field. At small values, it is $10^4 \dots 10^6$ Ohm·m and almost the entire voltage is added to it. When the field strength increases, the conductivity of the blocking layer increases sharply and the total resistance of the resistor begins to be determined by carborundum grains [104].

Nonlinear resistors of valve arresters are pressed in the form of disks from the initial mass consisting of silicon carbide powder and a binder. Currently, Vilite and

Tervit discs are used. Liquid glass is used as a binding material for the production of vilite discs, which allows the disc blanks to be fired at a relatively low temperature (about 300°C). Tervite disks, in which the binder is a mixture of liquid glass and alumina, are burned during manufacture at a temperature of 1000° C. At the same time, part of the SiO₂ barrier films burns out, which leads to a certain deterioration of the nonlinearity of the resistors, but their bandwidth increases significantly, that is, the ability to repeatedly pass without damage by large currents.

It is customary to characterize the volt-ampere characteristic of nonlinear resistors by a power-law dependence [104]:

$$U = C I^{\alpha},$$

where C is a constant that takes into account the properties of the material and the size of the resistor;

α - coefficient of nonlinearity of the material, which has different values in the area of small and large currents.

As follows from the given dependence, it is expedient to construct the current-voltage characteristic in logarithmic scales, in which it is represented by segments of a straight line. In fig. 5.2 shows a typical current-voltage characteristic of Vilite discs, which are used in arresters of the RVS type. The characteristic was taken at pulses of 20/40 μ s.

Area B of the current-voltage characteristic corresponds to the area of large currents passing through the arrester during lightning overvoltages.

In this section, the nonlinearity coefficient α for willite is 0.1 ... 0.2, for tervite - 0.15 ... 0.25. Section A of the current-voltage characteristic corresponds to the area of accompanying currents and most of the currents of switching overvoltages. The coefficient α for this area is much higher: for vilite - 0.28 ... 0.3; for tervite - 0.35 ... 0.38 [104].

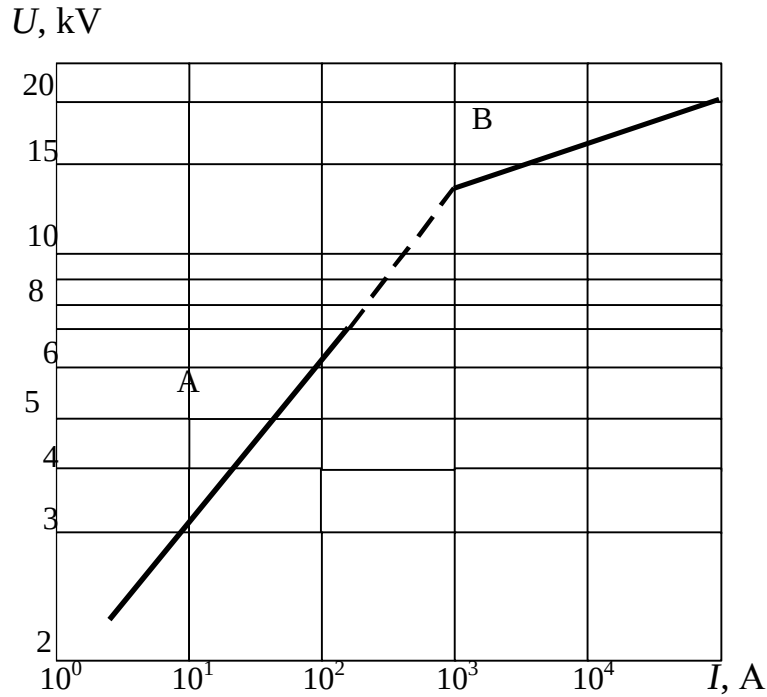


Figure 5.2 - IVA of the operating resistances of the valve arrester

The volt-ampere characteristic of a nonlinear resistance consisting of m resistors connected in series is written as

$$U = mCI^\alpha .$$

The values of C and α must be different for the two sections of the volt-ampere characteristic.

Non-linear overvoltage limiters

Currently used valve arresters with resistors based on silicon carbide due to the insufficient nonlinearity of the material do not allow for sufficient limitation of overvoltages [106, 107]. Their deeper reduction requires a decrease in the nonlinear series resistance, which leads to a significant increase in the accompanying currents. Spark gaps are unable to extinguish large currents. The inclusion of non-linear resistances under the operating voltage without spark gaps is impossible due to the large current due to the non-linear resistance at the phase voltage.

The use of spark gaps causes additional difficulties associated with the need to reduce the accompanying current to a value that can be reliably turned off by the gaps, as well as obtaining a smooth volt-second characteristic of the arrester.

A significant improvement in the protective characteristics of arresters can be achieved by abandoning the use of spark gaps. This turns out to be possible when switching to resistors with a sharply nonlinear current-current characteristic and sufficient bandwidth.

These requirements are met by varistors made of semiconductor material based on zinc oxide. The development and mass production of these varistors in the following years made it possible to develop protective devices with improved characteristics. Such devices, called surge protectors, are currently produced in a number of developed countries of the world. Surge arresters are mass-produced in Ukraine mainly for 6-110 kV networks. Currently, for networks with an isolated and resonantly grounded neutral, devices are produced in small batches, which is due to the demand of energy systems [108 - 110].

Currently, highly nonlinear zinc oxide varistors are mainly produced in the form of discs. ABB and EPCOS are considered the main manufacturers of varistors in the world.

The volt-ampere characteristics of such varistors are shown in Fig. 5.3, where the voltage is indicated in relative units, and the residual voltage on the varistor at a current of 100 A (U_{100}) is taken as the basic value.

The volt-ampere characteristic of nonlinear varistors is usually approximated by the dependence

$$U = CI^\alpha$$

where α is the nonlinearity coefficient of the material (nonlinearity index).

Nonlinear varistors made on the basis of zinc oxide and used in surge arresters are characterized by a significantly lower nonlinearity index α than silicon carbide ones

used in valve arresters. It should be noted that the α indicator strongly depends on the amount of current flowing through the resistance, and increases with increasing current [111].

Determination of the coefficient of nonlinearity α from the current-voltage characteristics of varistors has a large error due to the insufficient accuracy of the remaining voltage measurement. In order to calculate the nonlinearity coefficient with increased accuracy, a special circuit is used that allows measuring current pulses in parallel connected varistor columns, one of which is a reference.

By measuring the value of the resistance connected in series with the considered column, it is possible to vary the current in it within wide limits, while the current in the reference column maintains its amplitude. Increasing the accuracy of determining the voltage on the studied varistor column is determined by the high accuracy of measuring the current and voltage on it [112].

This is ensured by the control of the current in the reference column of the discs (some error in its measurement leads to a much smaller error in determining the voltage due to the small value of the coefficient α in the dependence ($U = CI^\alpha$), as well as by the more accurate measurement of the linear resistance connected in series with the column under study. The average values of the coefficient α obtained from the results of the measurements are shown in Table 5.2.

As can be seen from the table, the small value of α (0.015 ... 0.04), which determines the advantages of oxide-zinc varistors, covers the range of currents from 10^{-6} to 10^2 A. The passage of currents exceeding 500 A through varistors is undesirable, because in this case, the nonlinearity coefficient ($\alpha \geq 0.1$) increases sharply.

Table 5.2 - Average values of C and α parameters of oxide-zinc varistors

i, A	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10	100	500	1500
U/U_{100}	0,7	0,74	0,78	0,82	0,86	0,91	1	1,1	1,3
α	0,2					0,03	0,04	0,06	0,1
C/U_{100}	0,86						0,9	0,93	0,96

The volt-ampere characteristic of varistors allows you to complete non-linear surge arresters with improved protective characteristics without spark gaps. However, the absence of spark gaps determines the flow of 50 Hz currents through the OL at the operating voltage of the network. An excessive value of these currents can lead to overheating of varistors and failure of the OL [113].

The current flowing through surge arresters in normal mode contains capacitive and active components. At a voltage not exceeding $0.7U_{100}$, the capacitive component of the current prevails, which does not cause heating of the varistors. This corresponds to a voltage gradient of 1.0 kV / cm . With large voltage gradients, the nonlinear conductivity and the active component of the current increase sharply, which leads to significant heating of the varistors. The critical value of the operating voltage gradient of 1.0 kV / cm corresponds to the maximum permissible current through the varistor of $\sim 1 \text{ mA}$, which is mainly the conduction current, which is confirmed by the oscillograms of the current through the varistor at different voltages of 50 Hz.

The carrying capacity of OL s and the nature of their damage depend on the amplitude and duration of the current through them. When current pulses of long duration, characteristic of switching effects, flow through the OL, their significant heating is observed. The amplitude of the pulse that causes damage to varistors with a diameter of 28 mm is $80 \dots 120 \text{ A}$, and as a result of such actions, through-holes in varistors melt, and in some cases, varistors are destroyed. With short current pulses of $8/20 \text{ }\mu\text{s}$, characteristic of lightning overvoltages, varistors are not destroyed even under the influence of pulses with an amplitude of up to $1000 \dots 1500 \text{ A}$. A further increase in current leads to their overlap on the side surface, however, the overlap current can be significantly increased, if you cover the side surface of the varistors with a special insulating varnish or fill the varistors with a polymer compound. Data on the bandwidth of varistors in the mode typical for thunderstorm effects are given in table. 5.3.

In recent years, varistors of increased diameter (45, 60, and 85 mm) and, accordingly, greater bandwidth have been developed [114].

Non-linear overvoltage limiters are equipped with a large number of parallel and serially connected zinc oxide varistors. The number of varistors connected in series in the column and the number of parallel columns in the limiter are determined by the nominal voltage of the network and depend on the requirements for the protective level and the bandwidth of the limiters.

Table 5.3 - Transmitting capacity of oxide-zinc varistors under the influence of lightning surge impulses

Samples of oxide-zinc varistors (VR)	Capacity of varistors on current pulses of 8/20 μ s (20 pulses), kA
VR with a diameter of 28 mm	1,2 – 1,5
VR with a diameter of 28 mm (the side surface is covered with Glyphtal varnish)	2,2 – 2,5
VR with a diameter of 28 mm (filled with a polymer compound with a filler)	≥ 5
BP with a diameter of 60 mm	≥ 10
VR with a diameter of 60 mm (filled with a polymer compound with a filler)	≥ 25

When assembling varistor columns, it should be borne in mind that the voltage remaining on them depends on the steepness of the current pulses [115].

Features of lightning protection of lines with protected wires

The shielded wire consists of an aluminum twisted wire and a protective sheath (see Fig. 5.1). In some designs of shielded wires, a steel-aluminum wire is used, a wire consisting of a core in the form of a steel cable with aluminum wires wound on it. Aluminum wires can have the shape of irregular polygons with rounded edges to increase the density of filling the cross section of the wire with an active conductive

material (aluminum). Light-stabilized polyethylene is mainly used as a protective cover.

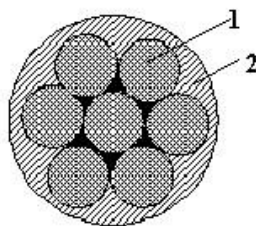


Figure 5.1 - Section of a protected wire; 1 - aluminum twisted wire; 2 - protective shell

The protective sheath provides short-term isolation of the wire in the event of tree branches touching it, when the wires cross under the influence of the wind, or when they are accidentally touched by foreign objects (for example, fishing rods, etc.). Overhead lines with shielded wires have greater operational reliability than lines with non-insulated wires [116 - 119].

In industrialized countries, PLs with shielded wires are becoming more and more common. In Japan, for example, all 6.6 kV substations are made with shielded wires. In recent years, construction of 6 - 35 kV substations with protected wires during reconstruction or new construction, which is provided for by the technical policy of Ukraine, has also been underway in Ukraine.

Under the influence of lightning overvoltage on the PL with non-insulated wires, the insulator overlaps (see Fig. 5.2, a). With a high probability, under the action of the operating voltage, the lightning overlap turns into an industrial frequency arc. As a result of electrodynamic forces, the arc moves along the wire. The arc burns until the line is disconnected or the arc extinguishes. Due to the fact that the arc moves along an uninsulated wire, wire burns by a power arc are relatively rare.

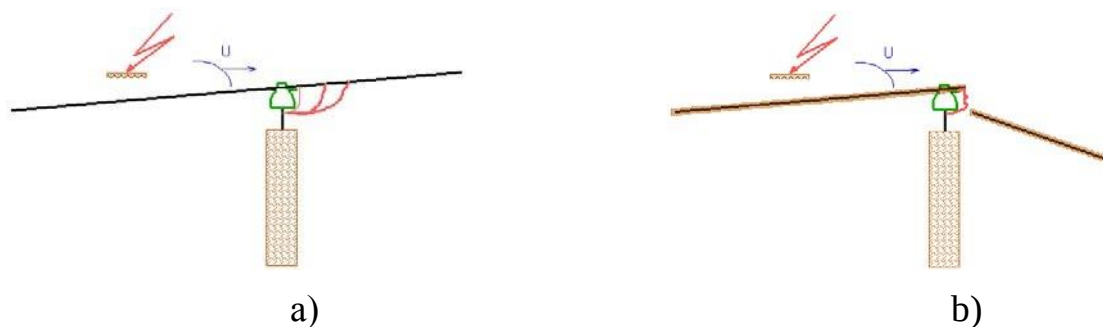


Figure 5.2 - Installation of a power arc of industrial frequency due to a lightning strike of the insulator: a) on a line with non-insulated wires; b) on a line with shielded wires

On a substation with protected wires, during a lightning overvoltage, the line insulator overlaps, and then - a breakdown of the solid insulation of the wire (see Fig. 5.2, b). Often, lightning overlap turns into an industrial frequency arc, which burns at the place of the insulation breakdown until the line is disconnected. In the case of large short-circuit currents or prolonged arc burning, this leads to wire burnout [120 - 123], i.e. to a serious accident on the line.

In the USA [120], it is proposed to remove the solid insulation in the section of the line near the support, and to install massive clamps on the border of the insulation (Fig. 5.3) for the lightning protection of a substation with protected wires.

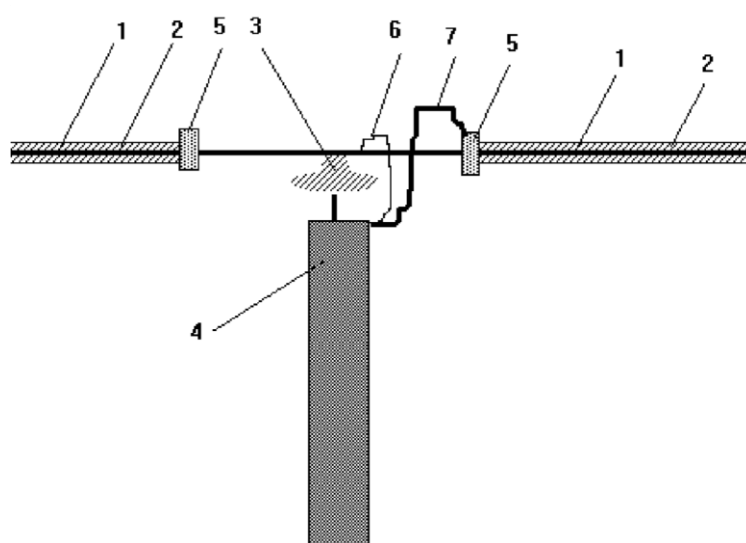


Figure 5.3 - Line protection against arcing damage using massive clamps (American system, [120]): 1 - wire, 2 - insulation, 3 - insulator, 4 - support, 5 - massive clamp, 6 - lightning cover, 7 – arc

In the event of an overvoltage, there is a lightning overlap 6 of the insulator 3 on an uninsulated section of the wire 1. This overlap turns into a power arc 7, which, under the action of electrodynamic forces, moves along the wire until it reaches the boundary of the insulation, on which a massive clamp 5 is installed. Then the arc does not move and continues to burn, resting with one of its ends on clamp 5, until the line is disconnected. In the case of a system with a grounded neutral (as, for example, in the USA), the short-circuit currents are very large, and the automation reacts relatively quickly to the short-circuit and disconnects the damaged line. However, there is significant burning of clamps 5, which determines the need for their periodic replacement. In addition, the formation of a power arc leads to the need to disconnect the line.

In Finland [121, 122], the system shown in fig. is used for lightning protection.

5.4.

In the event of an overvoltage, a single-phase overlap 6 to the ground occurs, and an arc 7 is formed, which moves along a metal spiral 8 wound on top of the insulation 2 of wire 1. Under the action of electrodynamic forces, the arc 7 passes to the corner 9 and then overturns to a nearby one (at a distance of approximately 30 - 40 cm) corner 9 of the adjacent phase (Fig. 5.4, a). In this way, a single-phase short-circuit is translated into a two-phase one.

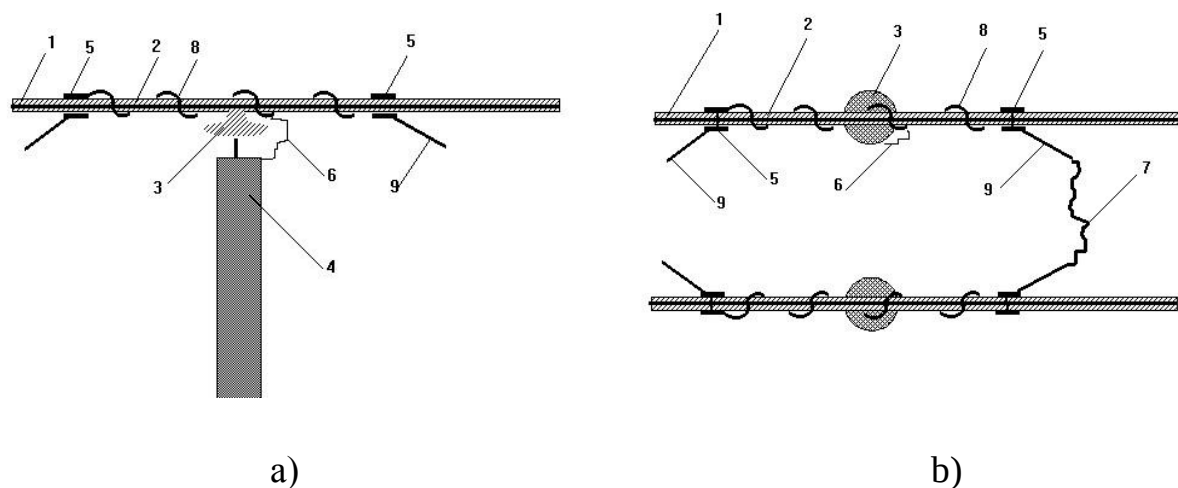


Figure 5.4 - Protection of the line against arc damage with the help of "horns" (Finnish system, [121]): a) side view; b) top view; 1 - wire, 2 - insulation, 3 - insulator, 4 - support, 5 - piercing clamp, 6 - lightning overlap, 7 - arc, 8 - spiral, 9 – horn

The arc of the two-phase short-circuit burns between the horns 9 until the line is disconnected, which leads to significant burning of the horns. Therefore, their periodic replacement is necessary. In addition, two-phase short-circuits create strong electrodynamic shocks on the windings of transformers, which leads to accelerated wear of their insulation and the entire equipment as a whole. Frequent commutations also increase costs for preventive revisions of switching equipment.

In Japan [123 - 126], non-linear surge arresters (OPS) have become widely used for lightning protection of overhead lines (Fig. 5.5). More than 6 million units have already been installed in just one of Japan's energy systems [124, 125].

The surge arrester is connected through a spark gap and is designed for a lightning overvoltage current of 2.5 kA. Surge arresters effectively limit induced overvoltages. But in the event that the lightning overvoltage current exceeds the calculated level, they are damaged.

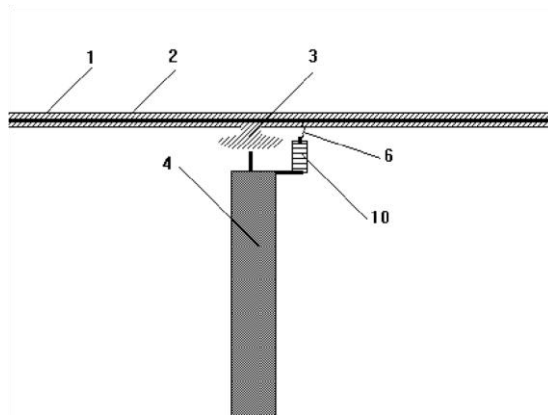


Figure 5.5 - Protection of the line against lightning overvoltages with the help of an arrester (Japanese system, [123]): 1 - wire, 2 - insulation, 3 - insulator, 4 - support, 6 - lightning overlap, 10 – arrester

For the most effective solution to the problem of lightning protection, it is highly desirable to install an arrester parallel to each insulator. With mass installation, the main disadvantage of OL is their high cost.

All of the above determines the need to find new technical solutions that increase the reliability and economic efficiency of lightning protection measures.

NPO "Strymer" has developed and patented in Russia, as well as abroad, a new method of lightning protection, based on the use of a long spark arrester (LSA), simple in design and, as a result, reliable and cheap devices [127 - 134]. LSA s are based on the principle of lengthening the channel of lightning protection and the absence of the possibility of establishing a power arc.

The main difference of long-spark arresters is their resistance to destruction and damage by lightning and arc currents, since they flow outside the devices, through the air along their surface.

This quality, which is unique for lightning protection devices, along with structural simplicity, made it possible to successfully use them as an effective and reliable means of protecting overhead lines and electrical networks from lightning surges and their consequences.

Long-spark arresters with a multi-electrode system (MES) [135] have been developed for lightning protection of 35 kV substations, which significantly increases the arrester's efficiency. The MES looks like (Fig. 5.6) a tape made of silicone rubber, on which electrodes with a diameter of 10 mm are fixed with gaps of 1-2 mm between them. The tape is wound on the LSA cable with a step of approximately 30 mm.

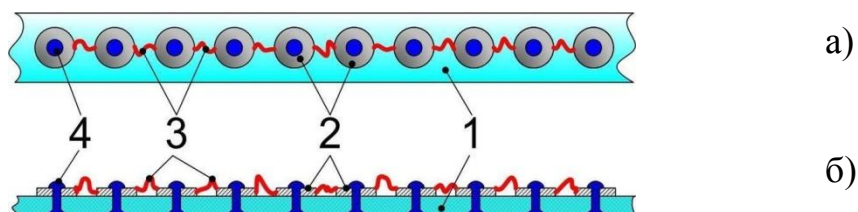


Figure 5.6 - Multi-electrode system: a) top view; б) side view; 1 - silicone rubber tape; 2 - electrodes; 3 - discharge channels; 4 - attachment of electrodes.

The increase in the efficiency of extinguishing the discharge channel is explained by two factors:

- cathodic voltage drop;
- by cooling the channel on the electrodes of the MES.

The arrester consists of two main elements: a loop and a loop, separated by a spark air gap. MES consisting of 500 electrodes each is installed on each of the elements. Thus, the total number of electrodes is 1000. During a lightning overvoltage, the spark air gap between the loop and the loop, as well as their MES, overlaps. The wire becomes connected to the support through the MES of 1000 electrodes and elementary gaps. After the passage of the lightning overvoltage current, the discharge channel extinguishes without the accompanying current of industrial frequency.

LSA 35 kV with a multi-chamber system (RDI-MKS) [132].

A further increase in the efficiency of extinguishing the accompanying current was achieved thanks to the use of the so-called multi-chamber system (MCS), shown in Fig. 5.7.

Just like the MES (Fig. 5.6), the ISS consists of a large number of intermediate electrodes with air discharge gaps of 1-2 mm between them, but on top of the electrodes there is a layer of insulation about 4 mm thick. The intermediate electrodes are mounted inside the silicone rubber profile. Channels with a diameter of approximately 4 mm are made from the discharge gaps to the surface of the profile. Basically, these channels are gas discharge chambers [133].

Under the influence of overvoltage on the ISS, air gaps between the electrodes break through (Fig. 5.7, a). In the process of formation and development of spark channels, their expansion occurs at the speed of sound. Since the volumes of the discharge spark chambers between the intermediate electrodes are very small, a high pressure is created, under the influence of which the channels of spark discharges between the intermediate electrodes move to the surface of the insulating body and are then thrown out into the surrounding air discharger (Fig. 5.7, b).

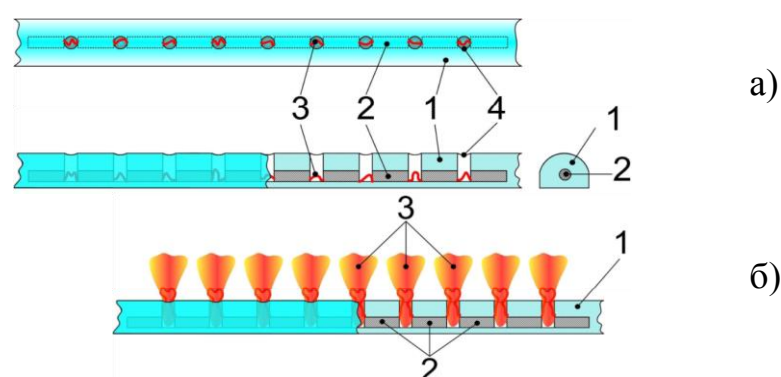


Figure 5.7 - Multi-chamber system: a) initial stage of discharge development; b) final stage; 1 - silicone rubber profile; 2 - electrodes; 3 - Discharge channels; 4 - gas discharge chambers

As a result of blowing and lengthening of the channels between the intermediate electrodes, the total resistance of all channels increases, i.e., the total resistance of the arrester increases, and there is a limitation of the impulse current of lightning overvoltage [134, 136].

After the end of the lightning overvoltage pulse, the industrial frequency voltage remains applied to the arrester. However, due to the high resistance of the discharger and due to the fact that the channel is divided into many elementary channels between the intermediate electrodes, the discharge cannot exist independently and extinguishes. The conducted studies showed that the efficiency of extinguishing the discharge of the ISS is approximately two times higher than that of the MEM. Tests have shown that for a 20 kV arrester, an ISS with $m = 200$ chambers is sufficient, and for a 35 kV - with $m = 500$ chambers.

Creation of a combined power transmission line

All methods of protecting PLs from lightning surges involve the installation of additional equipment, the presence of which leads to a decrease in the operational reliability of PLs due to an increase in the number of elements that can fail. Also, the installation of protective devices requires additional financial costs and operating costs. In addition, it should be noted that, as a rule, lightning strikes one phase of the PL. The mode of operation of PL of medium voltage classes involves an isolated or compensated neutral. In this case, a single-phase ground fault is not defined by regulatory documents as an emergency situation. This fact, as well as a significant reduction of the distances between the phases of the PPL, normalized by the PUE, makes it possible to consider another method of lightning protection than the installation of protective devices [137 - 139].

For more efficient and economical operation of PL with shielded wires, we suggest using a feature of lines of medium voltage classes, namely the use of an isolated neutral on these lines. On medium-voltage lines, a direct lightning strike will lead to a breakdown of the line insulation and a single-phase short circuit to the ground with 100% probability, due to the low impulse strength of the line insulation. The arc that occurs between the wire and the ground for such classes of voltage has the property of extinguishing due to external factors [139].

Conducted experimental studies of damage to PL and PPL on large-sized models showed differences in damage to non-insulated and protected wires. According to the results of experiments, it was determined that an uninsulated wire is more likely to be affected than a protected one [63 – 68, 83, 103].

Similar results led to the idea of creating a line that has both shielded and non-insulated wire in its design [103, 140]. This is due to the fact that the capture zone of an uninsulated wire is larger than the capture zone of a protected wire, which will lead to a significant redistribution of lightning strikes in the non-insulated wire. This fact was confirmed by experimental studies, which makes it possible to develop a lightning protection system of the PPL by using one non-insulated wire as a phase conductor. With such a design of the PPL, it is possible to predict that lightning strikes will mainly be on an uninsulated wire. Since, basically, the wires on the support are located in a triangle, the middle phase is higher than the extreme ones, it is recommended to perform it with an uninsulated wire, and to perform the extreme phases with protected wires, which will protect the protected wires from damage by direct lightning strikes and their burning due to the presence of an electric arc. This circumstance will make it possible to significantly improve the operational characteristics and safety of such a line. The proposed version of the location of the wires on the support is shown in Fig. 5.7.

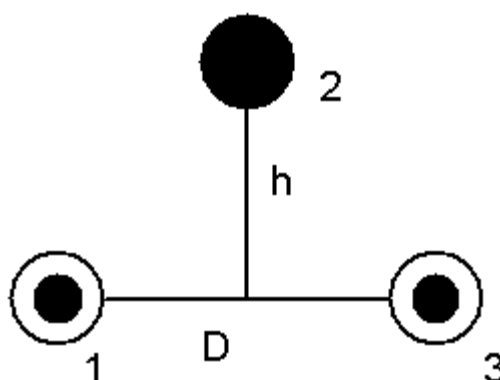


Figure 5.7 - Diagram of the location of the wires of the combined power transmission line. 1 - protected wire, 2 - non-insulated wire, 3 - protected wire, h - excess of the middle wire over the extreme ones, D - the distance between the extreme wires

To confirm the possibility of using a phase non-insulated wire as a lightning protection device, an experimental model of a combined power transmission line was created in the large high-voltage hall of the National Technical University "Kharkiv Polytechnic Institute" taking into account the similarity criteria obtained in Chapter 2 [141].

The following parameters were chosen to build the model:

- the lightning current is equal to 10 kA;
- line voltage - 6 kV.

A study of the lightning damage of the combined line was carried out taking into account the change in h and D .

An experiment matrix was created for conducting experimental studies, Table 5.1

Table 5.1 - Matrix of the experiment

	h	D	X
1	-	-	-
2	-	+	-
3	+	-	-
4	+	+	-
5	-	-	+
6	-	+	+
7	+	-	+
8	+	+	+

where "-" is the minimum value:

- 0 m for exceeding the average phase over the extreme ones;
- 0.1 m for the distance between extreme phases;

- 0 m for displacement of the electrode simulating lightning from the axis of the line.

"+" is the maximum value:

- 0.2 m for exceeding the average phase over the extreme ones;

- 0.3 m for the distance between extreme phases;

- 0.4 m for the displacement of the electrode simulating lightning from the axis of the line (zone of capture of non-insulated wire).

The experimental model had the following parameters: the height of the suspension of the electrode simulating lightning was equal to 1 m, the height of the suspension of the wires was 0.2 m, the excess of the average phase over the extremes varied from 0 to 0.2 m, the distance between the extreme phases varied from 0.1 to 0.3 m, the displacement of the lightning-imitating electrode relative to the line axis varied from 0 to 0.4 m, the middle phase was made with an AS - 50/8 wire, the extreme phases were made with a SIP-3 wire 1*50 – 20 [142].

8 series of experiments were performed, one series for each configuration, 100 experiments in each series. If the electrode is located above the line, all blows were to the non-insulated wire, if the electrode was located at a distance of 0.4 m (the zone of capture of the non-insulated wire) from the axis of the line, half of the blows were to the non-insulated wire, half to the ground. The obtained results make it possible to state that the degree of protection of the LVD by the non-insulated phase wire is quite high, as shown above, during 800 experiments, no discharge into the protected wire was obtained, which, in our opinion, is due to different mechanisms of damage to the protected and non-insulated conducted by a direct lightning strike. When the leader channel of lightning approaches an uninsulated wire, a charge of the opposite sign than that of the lightning collects on its surface, which contributes to the ionization of air in the direction of the leader channel and facilitates the development of counter-discharge from the wire to the leader, in the case of a protected wire, in the presence of a charge induced by lightning such of the same magnitude, the ionization process and the

development of the opposite leader is practically impossible, which is due to the presence of a protective coating and the complication of ionization processes.

The performed experimental studies of the combined line proved the high efficiency of protection of protected wires from burnout by using a non-insulated phase wire as a lightning arrester. In this way, we managed to correct the main shortcoming of PPL from the point of view of lightning protection, namely the possible burnout of protected wires due to a direct lightning strike to them. This fact gives us the opportunity to state that the combined line, while preserving all the advantages of PPL, will have the same lightning resistance as PL [141 - 144].

The operation of such a line does not require the installation of special devices for the protection of PL and PPL. The presence of one among the three phase wires, which is used as a lightning arrester, can be used to further increase the lightning resistance of the PL by increasing the electrical strength of the phase insulation. In addition, the use of a phase wire as a lightning arrester will allow to significantly increase the wave front impinging on the substation equipment due to pulse corona losses, and will allow to use this when calculating the reliability of the substation. Thus, in our opinion, the use of combined lines will solve several issues of lightning protection and will significantly reduce costs for the construction of lightning protection systems, which is a very relevant issue for Ukraine.

CONCLUSIONS

1. The possibility of using large-scale models for the study of induced overvoltages on overhead power lines is substantiated.
2. Lightning intensity issues and lightning current parameters, such as the length of the lightning current pulse and the growth rate of the pulse front, are very important for the development of lightning protection methods and measures
3. Experimental studies were conducted on large-scale models of the probability of a direct lightning strike on overhead line wires using protected wires and AS wires without a protective coating.
4. The analysis of the obtained results showed a significant decrease in the probability of a direct lightning strike in a line with protected wires, which indicates a greater lightning resistance of lines with protected wires.
5. On the basis of the obtained results, the method of calculating the number of direct lightning strikes on overhead lines was improved. This made it possible to clarify the lightning protection calculations of such lines at the design stage.
6. Taking into account the traditional design of lines of medium voltage classes with the placement of phase wires in a triangle, a combined power transmission line was created. This line contains in its design protected wires and a non-insulated wire, which acts as a lightning receiver, which allows you to predict the place of a lightning strike in the line and take the necessary measures to localize such a strike.
7. The methods and measures of lightning protection of overhead power lines of medium voltage classes are analyzed. The effectiveness of the use of the so-called long spark arresters is shown.
8. The obtained results made it possible to create a new approach to calculating the quantitative characteristics of lightning protection of overhead lines with protected wires.

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Ідентифікатор видавця в системі ISBN 8111

49000, Дніпро, 18, а/с 1212

тел. (096)-308-00-38, (056)-798-04-00

E-mail: 7980400@gmail.com