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ANALYSIS OF UNEXPLAINED BREAKS IN POWER TRANSMISSION LINES

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Abstract- In cable-protected lines, cases where the lightning conductor crosses the cable protection zone and directly hits the phase wire are also recorded. Such cases are observed in all voltage classes, and regardless of the voltage class, even when the amplitude value of the lightning current is 10-15 kA, the insulation of the line is covered and the line is automatically disconnected from the circuit. In such cases, although the line is connected to the circuit through an automatic reconnection device, sometimes the connection fails and uninterrupted supply of electricity to consumers is disrupted. Successful cases of electrical transmission lines (ETL) - automatic reconnection device of electrical transmission lines is usually recorded in the dispatcher's logbooks as unexplained trips. Also, the results of using modern non-linear overvoltage protection (NLOP) (suspension method) were investigated to increase the lightning resistance of EVX without cable protection.

Keywords: Electrical Transmission Lines (ETL), Electromagnetic Induction, Non-linear Overvoltage Protection (NLOP), Attachment Device, Lightning Protection, Pulse Coverage.

1. INTRODUCTION

The production and transmission of electricity is carried out and regulated in accordance with the relevant rules and laws of the state. Part of such rules also refers to the protection of those devices from internal and external overvoltage's in the energy system, including protection from atmospheric overvoltage's. Observance of these rules and laws, equipping the energy system with appropriate protective devices and devices enables uninterrupted supply of electricity to consumers. Since most of the power stations and substations of our republic's energy system, as well as electrical transmission lines (ETL), were built and put into operation during the former USSR, their protection from overvoltage's, including lightning (atmospheric) overvoltage's, is the rule, law, guidelines, and instructions in force at that time. and other materials were designed and built and put into operation.

Thus, as in the energy system of other countries included in the USSR, in the energy system of our Republic, the protection of stations and substations from direct lightning strikes was carried out by specially installed rod-shaped lightning arresters, and the protection of equipment from extreme voltages was carried out with appropriate valve dischargers.

Protection of ETL from direct lightning strikes is mainly by hanging one or two (depending on the construction of the supports) lightning protection wire from the support in different ways along the route in areas where the intensity of lightning is 20 hours or more on average during the year, depending on the construction of the line supports and the voltage class, in some cases, it was performed with tubular dischargers connected in parallel to the line insulators. In the substations located in the areas where the intensity of lightning is less than 20 hours, the length of 1-3 km of the lines is protected with a cable. Cable protection has proven itself in long-term operation and protected ETL from direct lightning strikes in most cases. However, during operation, it was recorded that as a result of various effects of the atmosphere (strong winds, freezing, corrosion, etc.), the cables sometimes break and fall on the phase wire, causing a short circuit, disconnection of the line, and interruptions in the supply of electricity to consumers.

In addition, in some cases, a lightning strike on the support of the line, at high values of the lightning current parameters, the insulation of the line is covered with a reverse arc and the line is automatically disconnected from the circuit. In cable-protected lines, cases where the lightning conductor crossed the cable protection zone and directly struck the phase wire were also recorded.

Such cases were observed in all voltage classes, and regardless of the voltage class, even when the amplitude value of the lightning current is 10-15 kA, the insulation of the line is covered and the line is automatically disconnected from the circuit. In such cases, although the line is connected to the circuit through an automatic reconnection device, sometimes the connection fails and uninterrupted supply of electricity to consumers is disrupted. Successful cases of automatic reconnection of ETL are usually recorded as unexplained trips in dispatcher logbooks.

Investigating such openings and taking appropriate measures to minimize their number is one of the most important issues. It should be noted that a number of results of the investigation of unexplained openings are given [1-4]. Here, for the investigation of the occurrences related to lightning, from the National Hydrometeorology Department of the "Ministry of Ecology and Natural Resources", the days with lightning recorded at 45 hydro meteorological stations currently operating in the territory of the Republic and the hours and minutes of the start and end of the lightning day recorded during the lightning day information has been obtained. Note that if there are several thunderclouds at different times during the day, the start and end times of each of them are recorded separately.

2. EXPERIMENTS AND CALCULATIONS

According to this rule, part of those openings is related to lightning discharges, and the remaining part of openings for unknown reasons are insulation of dew and pomegranate water drops sitting on the insulation of lines during foggy and drizzly weather in the morning (between 6-10 o'clock) in the spring and autumn seasons. It is determined that it is related to insulation coating due to increasing leakage currents. In order to perform a comparative analysis of the results we received, the length of each of the lines was adjusted to 100 km with the equation given below, and results related to lightning were additionally adjusted to 100 lightning hours:

$$n_{l\text{com}} = \frac{N_{act}}{T'L} \times 10^2 \tag{1}$$

$$n_{l.lig} = \frac{N_{act.lig}}{TLN_{lig.hour}} \times 10^4 \tag{2}$$

N_{act}: Actual number of unexplained openings recorded during the study period,
T: Research period, T=5 years,
L: The actual length of each researched ETL, km,
$N_{act.lig}$: The actual number of identified lightning-related openings on the line considered during the investigation;
$N_{lig.hour}$: The average value of the number of lightning hours recorded during the year on the route of the researched line, hours.

As we mentioned above, the results of the investigations conducted based on actual data are given in [5, 2]. As a result of the latest investigations of automatic trips of unknown reasons registered during the years 2005-2009, it was determined that about 14.6% of automatic trips of unknown reasons were recorded in 30 units of 110 kV ETL equipped with lightning protection cables of the power system. In 15 number 110 kV substations that are not protected by cables, about 22.1% of these openings are caused by lightning. In the present report, reports were made in the MATLAB program "Automated system of reporting lightning resistance of high and extremely high voltage ETL" (MB LinesPro 5.0) program, compiled and checked in order to check the compatibility of those results with the results performed according to the methodology given in [6].

In order to report with the specified program, supports of lines affected by lightning strike, insulation of the line, grounding resistance of supports, suspension height of the cable, suspension height of the wires on the support, axis of suspension of cables and wires, intensity of lightning on the track, etc. the data needs to be entered into the reporting program.

Therefore, the following information about each line is included in the program to make the report: ETL name, voltage, line length; wire type and radius; type of support, height and perimeter of half of the total height of the support; if the line is equipped with a cable, the type of cable, radius and height of suspension from the support; the average length of the passage between intermediate supports on the track; the average number of thunderstorm hours recorded during the year at weather stations along the route; the distance of the suspension of phases from the axis of the support; the height of suspension of the phases from the insulator chain on the support; type, number, chain height of insulators; +/– impulse breakdown voltage of insulator chain; the length of the leakage current path along the insulator chain; swing axes of phases and cable, height of phases and cable from the ground surface in the middle of the pass; the average value of the settlement resistance of the supports and specific resistance of the soil along route.

In general, the number of lightning strikes to ETL can be roughly calculated using a simpler the equation:

$$N = SnN_{lig.hour} \tag{3}$$

where, $N_{lig.hour}$ is average value of the number of hours of lightning during the year along the route of the line, hours;
n: The specific number of lightning strikes per 1 km^2 of the earth's surface in the area where the line's route passes during one lightning hour.

The specific number of lightning strikes per 1 km^2 of the earth's surface for plain regions with moderate climate is 0.05 [6], 0.06 [8], 0.067 [19] in various sources, and 0.01-0.02 [8] in mountainous areas has been accepted.

3. KEY CHARACTERISTICS FOR THE PROTECTION OF ETL FROM NLOP

When using NLOP for the protection of ETL, its main characteristics [7, 8] shown below should be examined first and their compatibility with the characteristics of the line should be checked.
– The maximum permissible operating voltage, kV;
– Rated voltage, kV;
– Volt-time dependence;
– Residual voltage (when lightning and switching impulse current pass through NLOP), kV;

The maximum allowable (long-term) working voltage, kV - NL is the largest effective value of the industrial frequency voltage that is continuously applied to it during the entire operational period of the OP. When a voltage greater than this voltage is applied, the current flowing through the NLOP begins to increase and can heat up its elements, causing damage to the device. According to normative documents, the value of the largest working voltage for networks of 110-220 kV is $\frac{1.15}{\sqrt{3}}U_{nom}$, for 330 kV $\frac{1.1}{\sqrt{3}}U_{nom}$ and for 500 kV $\frac{1.05}{\sqrt{3}}U_{nom}$ is determined and values are given in Table 1.

Table 1. Application to NLOP during normal operation of 110-500 kV networks the greatest working voltage

U_{nom}, kV	110	220	330	500
$U_{ə.b.i.}$, kV	73	146	210	303

$U_{ə.b.i.}$: In normal operation, NL is the largest operating voltage that can be applied to the OP for a long time.

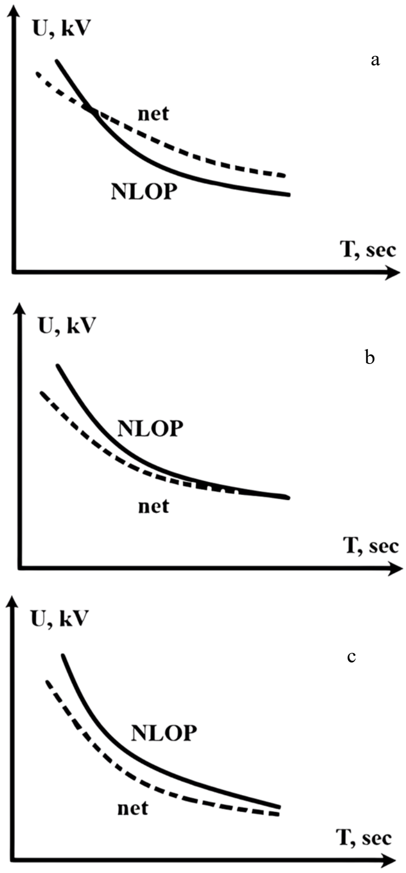

Figure 1. Correspondence graphs of the volt-time characteristic of the NLOP and the network where it is installed:
the volt-time characteristic of (a)-NLOP does not correspond to the volt-time characteristic of the network to be installed; the volt-time characteristic of (b)-NLOP corresponds to the volt-time characteristic of the network, that is, the NLOP is selected correctly; the volt-time characteristic of the (c)-NLOP is chosen with extra care to match the volt-time characteristic of the network

The nominal voltage of the NLOP is the effective value of the industrial frequency voltage that the NLOP can sustain for 10 seconds after being subjected to a normalized parameterized impulse current during the operational test. The rated voltage should be at least 1.25 times greater than the largest allowable working voltage [8,9]. The price of this voltage is not indicated by many manufacturers. Volt-time dependence - NL is a graph of the dependence of the industrial frequency voltage affecting the OP on the time it is applied to it. The points of the maximum allowable long-term operating voltage and nominal voltage of NLOP are the points of this dependence.

In general, the NLOP volt-time characteristic graph should always be higher than the grid's volt-time characteristic to ensure the safety of itself and the equipment it protects. Residual voltage, the volt-ampere characteristic of the kV – PANLO established during the impact of lightning and switching impulse current with a certain duration is determined in Figure 2.

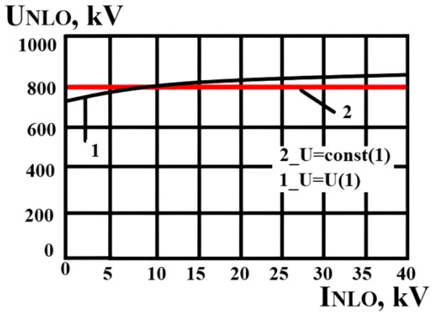

Figure 2. Volt-amer characteristic of PANLO and its simplified graph

The parameters of the pulse wave for extracting the volt-ampere characteristic under the influence of lightning impulse current are 8/20 mks and the parameters of the pulse wave are taken at 30/60 mks for the extraction of the volt-ampere characteristic under the influence of switching impulse current. The protection characteristic of NLOP depends on the duration of the pulse wave acting on it. Based on the volt-ampere characteristic set-in relative units, the non-linearity of the material of the varistors on which the NLOP is assembled is determined. In this characteristic, the current is related to the area of the varistor column, and the voltage is related to the amplitude of the largest working voltage $\sqrt{2} \cdot U_{gtw}$.

Therefore, the parameters of this characteristic practically do not depend on the height or diameter of the varistor column. Using the volt-ampere characteristic set-in relative units, it is possible to determine the typical frequency of lightning ($K_{8/20}$) and switching ($K_{30/60}$) overvoltage at the installation of NLOP. For the given greatest operating stress of the NLOP, these times allow to estimate the residual stress in the with some error by the Equations (4) and (5) [8].

$$U_{8/20} = \left(\sqrt{2}U_{gtw}\right) \times K_{30/60} \quad (4)$$

$$U_{30/60} = \left(\sqrt{2}U_{gtw}\right) \times K_{30/60} \quad (5)$$

In relative units, the amplitude of the largest working voltage $\sqrt{2} \cdot U_{gtw}$ applied to NLOP should not exceed the value of the limiting factor of extreme voltage during $K_{8/20}$ and $K_{30/60}$ shown in Table 2.

Table 2. Residual voltage during lightning and switching overvoltage

Voltage class, kV	110	220	330	500
Calculated current during lightning surge (impulse 8/20 μs), kA	10	10	10	20
Switching overvoltage (calculated current during pulse 30/60 μs), A	500	500	1000	1000
$K_{8/20}$	2.3			2.2
$K_{30/60}$	2.0			1.9

In addition to these specified characteristics, choosing its proper construction and insulation cover is an important issue, taking into account the variety of cone constructions of NLOP to be installed in ETL. Since the NLOP installed in ETL are mainly installed for lightning overvoltage protection, they are not considered for switching overvoltage during selection.

4. CALCULATION OF LIGHTNING PROTECTION

If there is a map of the average value of the number of lightning strikes per 1 km^2 of the earth's surface during the year, it is recommended to use the numbers recorded on the route of the line when calculating the lightning protection of the line. In the Equation (5), S -ETL is the width of the ground surface strip where lightning strikes are attracted and is calculated by Equation (6):

$$S = 6h_{or}L \times 10^{-3} \quad \text{km}^2 \tag{6}$$

where, Total length of L-ETL, km;

h_{ro}: The upper phase of the lightning protection cable (if there is no protection cable wire) is the average height from the ground surface (in flat areas from the ground surface of cables and wires in the middle of the passage between two intermediate supports height), in meters.

This height can be measured in different ways. The average height of the suspension of the cable (wires) from the ground surface can also be calculated by Equation (7):

$$h_{or} = h - \frac{2}{3} f \tag{7}$$

h: The height of the suspension of the wire (upper wire) from the support, in m;

f: The swing axis of the cable (overhead wire) during the lightning season, in m.

The height of suspension of the cable or top wire from the support is determined from the sketch of the support used in the reported line in the survey books or other literature. If there is no information about the swing axes of the cable (f_{ro}) or the top (f_{wir}^3) and bottom (f_{wir}^1) wires, their value can be determined approximately in the following the equation:

$h_{ro-wir} > h_{ro} - h_{wir}^3$ in case of

$$f_{ro} = h_{ro} - h_{\sup} - \left(h_{wir}^3 - h_{wir}^1\right) - h_{ro-wir} \tag{8}$$

where, $f_{wir} = h_{wir}^1 - h_{\sup}$, $h_{ro-wir} < h_{ro} - h_{wir}^3$ if it is:

$$f_{ro} = f_{wir} = h_{wir}^1 - h_{\sup} \tag{9}$$

h_{ro}: Suspension height of the cable from the support, m;

h_{wir}^3: Height of suspension of the upper wire from the insulator chain on the support, m;

h_{wir}^1: Height of suspension of the bottom (first from the bottom) wire from the insulator on the support, m;

h_{sup}: The smallest height allowed from the ground surface to the bottom wire between two intermediate supports according to the voltage class, m [7].

As we mentioned above, in order to check the conformity of the actual prices of lightning-related openings with prices and the lightning resistance of ETL, with the licensed software complex developed on the basis of the methodology recommended in [5], 110 kV lines where lightning-related openings were determined in 2005-2009 report has been completed. In this methodology, the number of lightning strikes on a 100 km ETL section is calculated using Equations (10) and (11): $h_{ro} \leq 30$ m when;

$$N = 0.2P_0\left(\frac{d_{ro-ro}}{2} + h_{ro} - \frac{2h_{ro}^2}{30}\right) \tag{10}$$

$h_{ro} \leq 30$ m, and when

$$N = 0.15P_0\left(\frac{d_{ro-ro}}{2} + h_{ro} + 90\right) \tag{11}$$

where,

h_{ro}: The average height of hanging the upper wire in the absence of a rope or a rope, calculated by Equation (5)-(7), m;

d_{ro-ro}: The distance between the cables (in the absence of cables, the upper wires), m. Alone d_{ro-ro}=0 is assumed for cable lines.

P_0: The density of lightning strikes per 1 km^2 of the earth's surface and is the average value of lightning hours during the year along the route of the line, and

$$P_0 = 0.05\ N_{th} \tag{12}$$

is calculated by Equation (12).

The total number of lightning strikes to the ETL is known to consist of three main parts: to the support, to the cable in the transition between two supports, and to the line wire crossing the protection zone of the cable. In the former USSR and the CIS countries, the intensity of lightning is calculated by the number of lightning hours in a year, and in foreign countries, it is calculated by the number of lightning days, which are essentially less different from each other. On average, one thunderstorm day is considered equivalent to 1.5 hours.

Meteorological observations of many years have shown that the average number of direct lightning strikes per 1 km^2 of the earth's surface is 0.4-0.6 strikes/km^2 during one lightning hour (1 T). constitutes an hour. Based on these data, the average number of lightning damage N of the 100-km-long ETL (electrical transmission lines) strip is calculated as follows:

$$N = \left(4 \div 6\right) h_{ro} \tag{13}$$

where, h_{ro} is the average height of the cable, or wire in ETL without a cable, from the ground surface, m. Currently, in the guidelines in force on the protection against extreme voltage, the width of the transmission line strip h_{ro} (6-80) is accepted.

The exposure of the Earth's surface to lightning strikes is somewhat selective; so that conductive objects above the ground (electrical or railway pylons, masts, technical devices, various constructions, etc.) are more affected by lightning.

Electrical equipment can be struck by lightning in the form of a direct strike or as a result of the corresponding electrostatic and electromagnetic induction of lightning currents. More dangerous is a direct lightning strike that directly strikes a live part and creates a voltage in it that can endanger the insulation. The direct shock current of lightning can create such a large voltage in the elements of the device with high grounding resistance and high inductance that a reverse discharge is formed from the parts connected to the ground to the current-carrying parts. The exposure of the Earth's surface to lightning strikes is somewhat selective; so that conductive objects above the ground (electrical or railway poles, poles, technical devices, various constructions, etc.).

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Extreme voltages due to electrostatic induction occur during lightning discharges; in this case, the neutralization or grounding charges in the cloud are in electrostatic contact with the free charges on the lines and other devices.

The faster the cloud discharges, the higher the induced voltage. However, this type of overvoltage is dangerous only for systems with a working voltage of up to 35 kV. Since the lightning discharge lasts for tens of microseconds, the charges released during this time have the opportunity to accumulate along the line; as a result, the amplitude and steepness of the voltage wave cannot reach a dangerous value.

Electrostatic effects associated with the leader process take on larger values if they occur in the vicinity of the object. In this case, depending on the proximity of the interacting charges, the induced overvoltage can reach dangerous values for the insulation, since the electric field changes rapidly in the first moments of the development of the lightning (head) discharge.

Electromagnetically induced overvoltage occurs when the opposite (main) discharge channel of lightning with its large-amplitude and rapidly changing currents is formed near current-carrying or grounded parts of the device. In such cases, a very high voltage may occur in those devices compared to the ground. Similar electromagnetic processes are observed when lightning strikes ETL supports and cables.

A lightning current falling on supports or cables induces a large-amplitude electromotive force in wires and metal structures near them. ETL are more prone to lightning strikes due to their length. Therefore, disruption of power systems, in most cases, occurs due to disruption of ETL insulation. In calculating the lightning resistance of ETL, the concept of the level of lightning resistance appears. This level, I_0, is characterized by the maximum amplitude of the lightning current and its steepness.

The lightning protection system must meet the technical requirements as well as the economic requirements. Costs spent on lightning protection, economic damage caused by interruptions in electricity supply, equipment failure in cases of lightning accidents, etc. should be a minimum.

The total number of lightning strikes (N) per 100 lightning hours of 100 km long lines during a year is calculated by the following equation:

$$N = 4h_{ro}\frac{n'}{100}\times\frac{l}{100} \tag{14}$$

where,

h_{or}: The average height of the cable or wire from the ground surface, m;

n': The number of lightning hours per year for a given location;

l: The length of the line, km.

Only a part of the mentioned damage can lead to covering of the insulation. The amplitude of the lightning current that creates the cover must be greater than the level of the lightning resistance of the given line, so the probable number of insulations covers:

$$N_1 = NP_i \tag{15}$$

where, P_i Is the probability of a lightning current that may exceed the lightning resistance level of the line insulation. The number of lightning damage to all technical installations and buildings not equipped with lightning protection devices in one year is generally determined by the following the equation:

$$N = \frac{(s+3h_x)\times(L+3h_x)n}{10^6} \tag{16}$$

where,

s: The width of the protected device, (m)

L: The length of the protected device (m)

h_x: Full height of the device from the side, (m)

n: The average number of lightning damage per 1 km^2 of the earth's surface, depends on the intensity of lightning activity (Table 3).

Table 3. Intensity of lightning activity

Number of hours of lightning in a year, hours	Average number of lightning injuries
20-40	2.5
40-60	3.8
60-80	5
80-100	6.3

The number of lightning hours in a year (on average) is determined from the map of lightning activity or on the basis of official data from meteorological stations.

4.1. Analysis of Cases of Lightning Damage to Overhead Lines

This type of overvoltage is dangerous for any type of insulation. To learn its characteristics, let's analyze cases of lightning damage to overhead lines, which are more exposed to atmospheric extreme voltages. First, let's look at the case of lightning damage to ETL mounted on metal supports. It is known that the electrical strength of the insulation is characterized by a 50% impulse discharge voltage during the impact of the impulse voltage.

Knowing the impulse discharge voltage of 50% of the phase insulation, it is possible to determine the level of protection of ETL laid on metal and iron-concrete supports when lightning strikes the wires of electric overhead lines:

$$I_{pro.} = \frac{U_{50\%}}{100} \tag{17}$$

After the impulse coating of the insulation, under the influence of the mains voltage, the short-term flow of the lightning current causes the closing of the electric arc with the ground. The probability that the impulse coating will turn into a stable arc discharge depends on the value of the nominal voltage of the network and the length of the coating path. In lines laid with metal and iron-concrete supports, the length of the surface discharge path is equal to the length of the chain of insulators, and the probability of arcing is high. For example, the probability of arcing in 110 kV lines is 0.6-0.7, that is, arcing occurs 6-7 times out of 10 impulse discharges, which creates a single-phase fault with the ground and causes automatic opening of the line. Let's look at the case of direct lightning strikes of line wires on tree supports. In this case, because the insulation of the wires from the ground is higher than that of the iron supports due to the wood, the probability of interphase covering is greater than that of grounding. The wave created by a lightning strike propagates along the damaged wire, creating an induced overvoltage in the neighboring wire. The value of the induced overvoltage depends on the coefficient of connection (K_{con}) of the wires. The voltage difference in interphase insulation is calculated according to the following rule:

$$U_{in} = 100' I_i \left(1 - K_{con}\right) \tag{18}$$

Protection level of lines laid on wooden supports without protective cable:

$$I_{pro} = \frac{U_{50\%}}{\left(1 - K_{con}\right)100} \tag{19}$$

Using lightning current probability curves, it can be found that only 37 out of 100 lightning discharges can result in insulation being covered. If we take into account that the probability of the impulse covering passing to a stable arc is less than 0.2, we see that only 7 out of 37 damages (0.2′36≈7) can cause the line to open. Finally, let's analyze the case of direct lightning strike of ETL-with cable protection (metal and iron-concrete supports are intended). For such lines, it is typical for lightning to fall on the cable in the immediate vicinity of the support; at this moment, a lightning current will flow from the ground connectors of the stand near the damaged area. The current flowing through the support is usually 70-80% of the lightning current. Based on this, the phase insulation voltage can be approximately found from Equation (20):

$$U_{in} = I_{\sup} r_{im} \approx 0.75\, I_i r_i \tag{20}$$

where,
U_{in}: Voltage in phase insulation, kV,
I_{sup}: Lightning current flowing through the support, kV,
r_i: The resistance of the connector with the ground, when the impulse current flows from it, with respect to the ground, Om,
I_{lig}: Is the calculation amplitude of the lightning current, kA.

Comparing the Equation (17) with that equation, it is possible to determine the level of protection of cable-protected lines:

$$I_{pro} = \frac{U_{50\%}}{0.75 r_{im}} \tag{21}$$

Thus, it can be seen that the greater the resistance of the grounding connector to earth, the lower the line protection level. Usually, r_i≤10 Ohm is taken in the calculations. In this case, the line protection level:

$$I_{pro} = \frac{U_{50\%}}{0.75'10} \approx 0.13 U_{50\%} \tag{22}$$

For example, for 110 and 220 kV lines, when the impulse discharge voltage of the phase insulation is 780 and 1500 kV, the protection levels are 0.13′780=100 kA and 0.13′1500=200 kA, respectively, which satisfy the norm. Induced voltages are created in the wires of the ETL - both during lightning strikes to the ground near the line, and when lightning strikes the supports and cables of the line. The answer to this is the rapid change of the electromagnetic field created by the lightning channel at the time of reverse discharge. In this regard, the induced overvoltage is divided into two summaries: electric (ro electrostatic) and magnetic accumulations caused by changes in the electric field at the moment of reverse discharge of lightning.

Consider the case of the formation of a voltage wave in the wires of the line due to the change of the electric field during the neutralization of the leader channel charges. When the leader channel approaches the ground with a relatively small speed, under the influence of the electric field of its negative charges, positive charges q from distant parts of the line in the wire are pulled to that part. As the negatively charged conductor descends, a positive charge is induced in the wire. Depending on how close the conductor is to the ground, the density of charges in the wires increases and their potential reaches the value U_0. The main (reverse) discharge channel of the conductor (channel neutralization) develops with great speed, and within a few microseconds the electric field of the conductor is destroyed. As a result, the charges on the lines are released and begin to disperse along the line. At the point of discharge $\frac{U_0}{2}$, two potential electromagnetic waves traveling in opposite directions along the line are formed. Induced over voltages are determined by the voltage on the interphase insulation, mainly by the difference in the distance between the wires in the phases.

For overhead lines with a working voltage of up to 35 kV, the interphase insulation distance is usually taken to be 2-2.5 m. The possibility of covering in the air distance is non-existent, in 6-35 kV lines built on metal and reinforced concrete supports, the danger of grounding on the supports remains because the covering path along the chain is short. Considering this, by increasing the number of elements in the chain of insulators (extending the closing path), the insulation level of those lines can be increased. It should be noted that the amplitude of induced over voltages rarely reaches 500-600 kV values. Based on many years of operating experience, it was possible to calculate the amplitude of the induced overvoltage for lines without cable protection using the empirical Equation (23):

$$U_{ind} = 25\frac{I_i h_{ro}}{a} \tag{23}$$

where,
I_i: Lightning current, kA
h_{ro}: The average height of the wire from the ground surface, m
a: Is the distance from the line to the place of lightning strike, m.

The presence of earthed cables reduces the cost of induced over voltages; so that the cables shield the wires in parts. As a result, a small load is induced on the wires. The value of induced over voltages in power lines equipped with protective cables can be determined by the Equation (24):

$$U'_{ind} = U_{ind}\left(1-k_1k_2\right) \tag{24}$$

where, k_1 is the connection coefficient, determined by the ratio of the mutual wave $\frac{z_{12}}{z_{11}}$ resistances of the wires:

$$z_{12} = \frac{u_1}{i_2}\ ,\ \ z_{11} = \frac{u_1}{i_1}$$

The k_2 is a factor taking into account the effect of crowning, its values are taken from Table 4.

Table 4. Values of the crowning coefficient of K_2

Number of ropes	$U_{ind,\,kq}$		
	35	110	220
A rope	1.1	1.2	1.3

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4.2. Investigating Unexplained Openings

Since most of the power stations and substations of our Republic's energy system, as well as power transmission lines (ETL), were built and put into operation during the former USSR, their protection from over voltages, including lightning (atmospheric) over voltages, is the rule, law, guidelines, and instructions in force at that time. and other materials were designed and built and put into operation.

Thus, as in the energy system of other countries included in the USSR, in the energy system of our Republic, the protection of stations and substations from direct lightning strikes was carried out by specially installed rod-shaped lightning arresters, and the protection of equipment from extreme voltages was carried out with appropriate valve dischargers.

Protection of ETL from direct lightning strikes is mainly by hanging one or two (depending on the construction of the supports) lightning protection wire from the support in different ways along the route in areas where the intensity of lightning is 20 hours or more on average during the year, depending on the construction of the line supports and the voltage class, in some cases, it was performed with tubular dischargers connected in parallel to the line insulators. In the substations located in the areas where the intensity of lightning is less than 20 hours, length of 1-3 km of lines is protected with a cable.

Cable protection has proven itself in long-term operation and protected ETL from direct lightning strikes in most cases. However, during operation, it was recorded that as a result of various effects of the atmosphere (strong winds, freezing, corrosion, etc.), the cables sometimes break and fall on the phase wire, causing a short circuit, disconnection of the line, and interruptions in the supply of electricity to consumers.

In addition, in some cases, a lightning strike on the support of the line, at high values of the lightning current parameters, the insulation of the line is covered with a reverse arc and the line is automatically disconnected from the circuit. In cable-protected lines, cases where the lightning conductor crossed the cable protection zone and directly struck the phase wire were also recorded.

Such cases were observed in all voltage classes, and regardless of the voltage class, even when the amplitude value of the lightning current is 10-15 kA, the insulation of the line is covered and the line is automatically disconnected from the circuit. In such cases, although the line is connected to the circuit through an automatic reconnection device, sometimes the connection fails and uninterrupted supply of electricity to consumers is disrupted. Successful cases of automatic reconnection of ETL are usually recorded as unexplained trips in dispatcher logbooks. Investigating such openings and taking appropriate measures to minimize their number is one of the most important issues. It should be noted that a number of results of the investigation of unexplained openings are given [1, 2].

Here, the "Ministry of Ecology and Natural Resources" for the investigation of lightning-related openings. From the National Department of Hydrometeorology in the territory of the Republic. At 45 currently operating hydrometeorological stations, information was obtained on the days with thunderstorms and the hours and minutes of the beginning and end of the thunderstorm day recorded during the thunderstorm day. Note that if there are several thunderclouds at different times during the day, the start and end times of each of them are recorded separately.

According to this rule, part of those openings is related to lightning discharges, and the remaining part of openings for unknown reasons are insulation of dew and pomegranate water drops sitting on the insulation of lines during foggy and drizzly weather in the morning (between 6-10 o'clock) in the spring and autumn seasons. it is determined that it is related to insulation coating due to increasing leakage currents.

In order to perform a comparative analysis of the results we received, the length of each of the lines was adjusted to 100 km with the equation given below, and the results related to lightning were additionally adjusted to 100 lightning hours:

$$n_{x.(com)} = \frac{N_{act}}{TL} \times 10^2 \quad (25)$$

$$n_{x.light} = \frac{N_{act.ligh.}}{TLN_{th.hour}} \times 10^4 \quad (26)$$

where,

N_{act}: The actual number of unexplained openings recorded during the research period

T: Research period, T=5 years

L: The actual length of each researched ETL, km

$N_{act.light}$: The actual number of openings determined due to lightning on the considered line during research period

$N_{thun.hour}$: Is the average value of the number of lightning hours recorded during the year along the route of the researched line, hour.

As we mentioned above, the results of the investigations conducted based on actual data are given in [1, 2]. As a result of the latest investigations of automatic trips of unknown reasons registered during the years 2005-2009, it was determined that about 14.6% of automatic trips of unknown reasons were recorded in 30 units of 110 kV, ETL equipped with lightning protection cables of the power system. In 15 number 110 kV substations that are not protected by cables, about 22.1% of these openings are caused by lightning.

In this report, in order to check the compatibility of the results performed according to the methodology given in [3], the reports were made in the MATLAB program system of reporting of lightning resistance of high and extremely high voltage ETL (MB Lines Pro 5.0) licensed program, compiled and checked.

In order to report with the specified program, supports of lines affected by lightning strike, insulation of the line, grounding resistance of supports, suspension height of the cable, suspension height of the wires on the support, axis of suspension of cables and wires, intensity of lightning on the track, etc.

The data needs to be entered into the reporting program. Therefore, the following information about each line is included in the program to run the report: ETL name, voltage, line length; wire type and radius; type of support, height and perimeter of half of the total height of the support; if the line is equipped with a cable, the type of cable, radius and height of suspension from the support; the average length of the passage between intermediate supports on the track; the average number of thunderstorm hours recorded during the year at weather stations along the route; the distance of the suspension of phases from the axis of the support; the height of suspension of the phases from the insulator chain on the support; type, number, chain height of insulators; +/- impulse breakdown voltage of insulator chain; the length of the leakage current path along the insulator chain; swing axes of phases and cable, height of phases and cable from the ground surface in the middle of the pass; the average value of the settlement resistance of the supports and the specific resistance of the soil along the route.

In general, the number of lightning strikes to ETL can be roughly calculated using a simpler Equation (27):

$$N = SnN_{thun.hour} \quad (27)$$

where,

$N_{thun.hour.}$: The average value of the number of lightning hours during the year along the route of the line,

n: The specific number of lightning strikes per 1 km^2 of the earth's surface in the area where the line's route passes during one lightning hour. The specific number of lightning strikes per 1 km^2 of the earth's surface for plain regions with mild climate is 0.05 [6], 0.06 [8], 0.067 [9] – in different sources, and 0.01-0.02 [8] in mountainous areas has been accepted.

5. DISCUSSION

In cable-protected lines, cases where the lightning conductor crosses the cable protection zone and directly hits the phase wire are also recorded. Such cases are observed in all voltage classes, and regardless of the voltage class, even when the amplitude value of the lightning current is 10-15 kA, the insulation of the line is covered and the line is automatically disconnected from the circuit.

In such cases, although the line is connected to the circuit through an automatic reconnection device, sometimes the connection fails and uninterrupted supply of electricity to consumers is disrupted. Successful cases of automatic reconnection of ETL are usually recorded as unexplained trips in dispatcher logbooks. Investigating such openings and taking appropriate measures to minimize their number is one of the most important issues.

The results of the studies performed in [10] show that for 110 kV ETLs, the influence of the method of connecting the device to the wire on the device during lightning overvoltage is negligible. This is due to the fact that the spark gap of PANLO in 110 kV ETL is pierced by the lightning wave generated during all lightning strikes close to the area where the device is installed, and for this reason, the spark gap generated in PANLOs installed at 110 kV with or without a spark gap process are shown to be close to each other in character.

6. CONCLUSIONS

1. Depending on the probability of lightning strikes, PANLOs can be installed both on cabled and cableless YG lines.
2. Lightning protection of high voltage lines mainly depends on the scheme of placement of PANLO on the line and grounding resistance.
3. In case of high internal (switching and quasi-stationary) overvoltage's, PANLOs can be placed with a spark gap. The inclusion of spark gaps in the scheme increases the effectiveness of lightning protection of high voltage lines.

NOMENCLATURES

1. Acronyms

ETL	Electrical Transmission Lines
HVL	High Voltages Lines
PANLO	Protection Against Non-Linear Over voltages
NLOP	Non-Linear Overvoltage Protection

2. Symbols / Parameters

N_{act}: The actual number of unexplained openings recorded during the study period;
T: Research period;
L: The actual length;
$N_{act.lig}$: The actual number of identified lightning-related openings;
$N_{lig.hour}$: Average value of number of lightning hours;
N: Is the specific number;
h_{ro}: The upper phase of the lightning protection cable;
h: The height of the suspension of the wire (upper wire) from the support;
f: Swing axis of the cable (overhead wire) during the lightning season;
h_{wir}^{3}: Height of suspension of the upper wire from the insulator chain on the support;
h_{wir}^{1}: Height of suspension of the bottom (first from the bottom) wire from the insulator on the support, m;
h_{sup}: The smallest height allowed from the ground surface to the bottom wire between two intermediate supports according to the voltage class;
$d_{ro\text{-}ro}$: The distance between the cables;
P_0: The density of lightning strikes per 1 km^2 of the earth's surface;
l: The length of the line;
h_x: Full height of the device from the side;
n: The average number of lightning damage;
U_{in}: Voltage in phase insulation;
I_{sup}: Lightning current flowing through the support;
r_i: The resistance of the connector with the ground;
I_{lig}: The calculation amplitude of the lightning current;
N_{act}: The actual number of unexplained openings recorded during the research period;
T: Research period;
$N_{thun.hour}$: The average value of the number of lightning hours recorded during the year along the route of the researched line

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