1. Elbrus AHMEDOV[1], 2. Sona RZAYEVA [2], 3. Nigar GANIYEVA[3], 4. Elshad SAFİYEV[4]

Azerbaijan State Oil and Industry University (1, 2, 3,4)
ORCID: 1.0000-0003-3348-7946; 2. 0000-0001-7086-9519; 3. 0000-0002-3729-102X

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Improving the lightning resistance of high-voltage overhead power line

***Abstract**. In the presented article, by the method of planning an experiment, an analysis of the parameters that affect the stability of high-voltage overhead power lines to the effects of atmospheric overvoltages was carried out. The parameters that have a greater impact on the reliability of high-voltage overhead power lines from lightning surges are determined. Partially changing the design of the ground wire, a new effective method was proposed to increase the protection zone by winding longitudinal metal rods in the shape of the letter "V" on its surface. The possibility of increasing the lightning protection zone by placing these simple elements on the surface of the ground wire is shown, in addition, the possibility of further reducing the probability of the passage of the lightning channel bypassing the ground wire and directly falling into the conductor due to the increase in the inhomogeneity of the electric field between the ground wire and the lightning rod.*

Streszczenie.** W prezentowanym artykule metodą planowania eksperymentu przeprowadzono analizę parametrów wpływających na stabilność napowietrznych linii elektroenergetycznych wysokiego napięcia na skutki udarów atmosferycznych. Określono parametry, które mają większy wpływ na niezawodność napowietrznych linii elektroenergetycznych wysokiego napięcia od wyładowań atmosferycznych. Po częściowej zmianie konstrukcji kabla odgromowego zaproponowano nową skuteczną metodę zwiększenia strefy ochronnej poprzez nawinięcie na jego powierzchnię podłużnych metalowych prętów w kształcie litery „V". Pokazano możliwość zwiększenia strefy ochrony odgromowej poprzez umieszczenie tych prostych elementów na powierzchni przewodu odgromowego, dodatkowo możliwość dalszego zmniejszenia prawdopodobieństwa przejścia piorunochronu wokół przewodu odgromowego i bezpośredniego uderzenia w przewód dzięki pokazano wzrost niejednorodności pola elektrycznego między przewodem uziemiającym a piorunochronem. (Poprawa odporności odgromowej napowietrznej linii elektroenergetycznej wysokiego napięcia**)

Keywords: high voltage overhead lines, lightning overvoltages, number of lightning strikes, ground wire.
Słowa kluczowe: linie napowietrzne wysokiego napięcia, przepięcia wyładowań atmosferycznych, liczba uderzeń piorunów.

Introduction

Insulation of overhead power transmission lines (OHTL) during operation is subjected to active and various types of overvoltage, in which atmospheric influences play an important role. A lightning strike on power lines can cause significant damage to these power lines, power outages, and disruption of daily life. As you know, due to climate change in the world, in some regions there are cases of an increase in the intensity of thunderstorms. Studies have shown that as the planet's temperature continues to rise, the intensity and frequency of thunderstorms have also increased in some regions. In recent years, there has been a growing body of research into the relationship between climate change and thunderstorms. The research team used simulations of the impact of climate change on thunderstorms and found that by the end of the century, the number of days with severe thunderstorms could increase by 40% [1-3]. Other studies have shown that the intensity of thunderstorms in Europe may increase due to climate change. Higher temperatures and higher humidity can create more favorable conditions for the development of thunderstorms, and changes in atmospheric circulation patterns can also contribute to more intense thunderstorms [4-6].

An increase in the frequency and intensity of thunderstorms can have serious consequences, including property damage, power outages, and even loss of life. As climate change continues to affect our planet, it is important to understand its impact on thunderstorms and take steps to mitigate its effects. Considering the above, improving the lightning resistance of overhead power lines is currently an important task that requires a combination of design, construction and maintenance strategies. By reducing the risk of damage from lightning strikes, utilities can increase the reliability and security of their power systems by helping ensure power is available when and where it is needed.

As is known, OHTL is very long-distance, which increases the possibility of lightning surges, which can lead to disruption of the power system. For this reason, effective protection of OHTL from lightning effects is one of the most urgent issues. Therefore, the analysis of lightning overvoltages occurring in electric power systems is of great importance, as it provides reasonable opportunities for optimizing the construction and installation of OHTL and high-voltage substations, reducing costs, and increasing the reliability of electric power transmission and distribution. According to international statistics, 50-70% of all unplanned outages of overhead power lines are caused by lightning strikes. With an increase in the voltage class of overhead lines, despite a decrease in the number of disconnections from lightning surges, the proportion of disconnections from lightning surges in the total number of disconnections increases [7, 8]. Therefore, increasing the stability and reliability of OHTL from lightning discharges is one of the important issues in providing consumers with uninterrupted power supply.

Problem setting

With a direct lightning strike into the phase conductor of an OHTL, overvoltage waves are formed in the line and propagate along the wire in both directions. If lightning strikes a line near a substation, the resulting overvoltage wave creates a great danger to the substation equipment. The amplitude of the voltage wave is limited by the breakdown voltage of the linear insulation of the OHTL. The weakest link in an OHTL is considered to be a chain of insulators [9]. In this regard, the maximum lightning wave voltage is determined by the discharge voltage of the insulator circuit.

The most dangerous situation occurs when a direct lightning strike strikes a high-voltage OHTL (Fig. 1). In this case, an overvoltage is created in the line, and the possibility of closing the insulators increases. As a result, the insulators may be short-circuited. When lightning strikes an overhead line near a substation, there is a danger to the substation equipment.

When the number of thunderstorm hours in the area of overhead lines is more than 20 hours per year, power lines placed on iron and reinforced concrete supports with a voltage of more than 35 kV are equipped with lightning protection cables. The number of these lightning protection cables depends on the voltage class, the resistance of the earth on which the support is located, the number of phase wires on the support, and other factors. Depending on the distance (α -protection angle) between the ground wires and the nearest phase conductor, the height of the protective cable hanging on the support is determined. The reported results of the distribution of lightning discharges at points 1, 2, and 3 of the overhead lines (Fig. 1) according to different methods are given in Table 1 [10, 11].

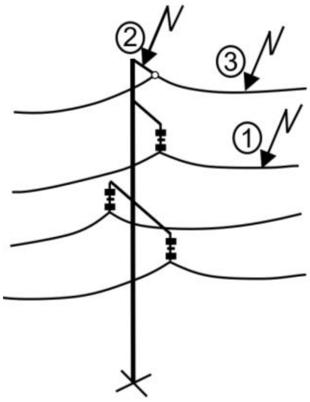

Fig. 1 Direct strike of an overhead power line by lightning

Table. 1 The occurrence of lightning discharge in different elements of OHTL

Lightning strike points	Location of the lightning strike	There is no ground wire	Ground wire installed
1	Phase wire	0.5	0.005
2	Striking in towers or ground wire near the tower	0.5	≈0.5
3	Ground wire in the middle of the span	0	≈0.5

As can be seen from Table 1, the installation of a ground wire on the lines reduces the likelihood of a direct lightning strike into the phase conductor by 100 times and significantly increases the lightning resistance of overhead lines. However, when lightning strikes a pole or a ground wire, the insulation may break due to the rise in the impulse potential at the point where the circuit of the phase wire insulators is attached to the traverse. At the same time, there is always a possibility that lightning will bypass the ground wire and strike directly into the phase conductor.

The critical value of the lightning current, which leads to a short circuit of the line insulation when the lightning bypasses the ground wire and enters directly into the phase conductor, is not very large. The lightning current of the 110–330 kV OHTL closes at an amplitude of 3–10 kA. Lightning currents of 15–35 kA pose a threat to the insulation of OHTL of 500–1150 kV. Almost every lightning strike into the phase wire of a 110 kV overhead line causes a short circuit [12].

Thus, to increase the lightning resistance of an OHTL, the following means are used:

- use of grounded lightning rods;
- reduction of grounding resistance of supports;
- increasing the impulse electrical strength of line insulation;
- protection of poles in places with poor insulation and are more prone to lightning strikes;
- application of surge arresters [13].

High-speed automatic reclosing is one of the backup tools that ensure the uninterrupted and reliable operation of an overhead power transmission line. According to operating experience, the automatic reclosing success rate is 0.6 to 0.8 for 110 to 500 kV lines and 0.8 to 0.9 for 750 and 1150 kV lines. Automatic reclosing partially compensates for the low level of lightning resistance of the transmission line. However, the use of automatic reclosing should not preclude the use of ground wires. Thus, short circuits reduce the life of electrical equipment.

One of the main means of reducing the probability of a pulsed short circuit in the event of a direct lightning strike into a ground wire or a pole is to reduce the grounding resistance of an overhead line pole. In cases where the earthing resistance of the support is high, special lightning rods with a higher conductivity should be used. During this time, the lightning current flows to the ground with less resistance, which reduces the chance of an insulation short circuit and accidental opening.

Recently, the issue of using a new type of lightning protection system for overhead lines has been considered. Here, instead of regular ground wires, additional ground wires are used, which are installed on supports located in parallel on both sides of the protected overhead power line. However, in such a protection system, an additional design is used, which is used in special cases to protect only short sections of overhead lines [14].

Another way to increase the lightning resistance of OHTL is to use surge arresters. In this case, the surge arresters are installed directly on the OHTL poles. The use of surge suppressors is more effective in conditions of high ground resistance at towers and on high towers.

Economic calculations have shown that it is more expensive to protect overhead lines along the entire length of the highway without using lightning protection cables than with the use of surge arresters. In addition, when lightning strikes an overhead line, the current on the surge arresters is high, so the likelihood of their failure increases. Therefore, in such a case, surge arresters capable of discharging higher currents (>1000 A) should be used. However, this, in turn, leads to a further increase in the cost of the project. During the construction and reconstruction of 110–750 kV overhead lines, to increase lightning protection, the installation of surge arresters on supports should be considered an additional tool and should be technically and economically justified.

Solutions to the problem

The number of lightning strikes that can directly strike an overhead line depends on various factors, primarily the length of the line and the lightning intensity. As mentioned above, the main danger for overhead lines occurs when lightning directly hits the line and can be conditionally divided as follows:

- a lightning strike into the phase conductor (Fig. 1, point 1);
- a lightning strike into the supports (Fig. 1, point 2);
- a lightning strike into the ground wire (Fig. 1, point 3).

The average number of lightning strikes on 110–220 kV overhead lines is calculated using different methods [15–17]. The number of lightning strikes on an overhead power line during the year is determined by the following formula:

$$(1)\quad n_{th.n} = 4 \cdot h_{gr.w.ov} \cdot \frac{L_{tl}}{100} \cdot \frac{D_{y.n}}{100}$$

where $h_{gr.w.ov}$ -average suspension of a ground wire *m*; L_{tl}-length of overhead power line,*km;* $D_{y.n}$- number of thunderstorm hours per year.

In order to detect and analyze the number of lightning strikes and the factors that have a greater impact on these strikes, the relevant parameters for a single-circuit 110 kV overhead line ($h_{gr.w.ov}$ =14.17 m; L_{tl}=120km; $D_{y.n}$=25 let's take hours) into account in expression (1). By doing the appropriate calculations, we find that the probability of the line being struck by lightning during the year is $n_{th.n}$=17 strikes/year.

To determine the parameters that have the greatest impact on the power line shutdown due to lightning, we analyze the parameters using the theory of statistical planning of mathematical experiments—the full factorial planning method. The method of full factorial planning of the experiment allows one to determine the mathematical expression of the process in the form of an approximation polynomial [18].

$$f\left(x_1,x_2,x_3\right)=b_0+\sum_{i=1}^{3}b_i x_1+\sum_{\substack{i,j=1\\ i\prec j}}^{3}b_{i,j},x_i x_j+b_{123}x_1x_2x_3 \quad (2)$$

In the formula (2), we can write for the Z_i coordinates:

$$\sum_{i=0}^{N-1}b_l Z_i=\sum_{i=0}^{7}b_l Z_i \quad (3)$$

Here we consider them as, (x_1=$h_{gr.w.ov}$; x_2=L_{tl} ; x_3= $D_{y.n}$), independent process variables. The planning of experiments should be carried out by constructing a matrix.

$$\sum_{g=1}^{N}X_{gl}X_{gi}=0;\ \sum_{g=1}^{N}X_{gi}=0;\sum_{g=1}^{N}X^2_{gi}=N \quad (4)$$

Here, N is the number of experiments, and g is the experiment number. The total number of planning experiments in the matrix is determined as $N=2^n$, where n is the number of variable factors, or parameters (table 2).

Table 2. Matrix of parameters influencing the shutdown of a power transmission line by lightning strikes

Experiment number №	n	X_0=17		$h_{gr.w.ov}$=14.17		L_{tl}=120		$D_{y.n}$=25		Z_1 Z_2	Z_1 Z_3	Z_2 Z_3	Z_1 Z_2 Z_3
		Z_0		Z_1		Z_2		Z_3					
1	8.7	17	+	11.34	-	96	-	20	-	+	+	+	-
2	13.06	17	+	17.0	+	96	-	20	-	-	-	+	-
3	13.06	17	+	11.34	-	144	+	20	-	-	+	-	-
4	19.58	17	+	17.0	+	144	+	20	-	+	-	-	-
5	13.06	17	+	11.34	-	96	-	30	+	+	-	-	+
6	19.58	17	+	17.0	+	96	-	30	+	-	+	-	-
7	19.59	17	+	11.34	-	144	+	30	+	-	-	+	-
8	29.38	17	+	17.0	+	144	+	30	+	+	+	+	+

Let's analyze the parameters that affect the resistance of overhead power lines against lightning surges based on the values of the coefficients of the following equation obtained from the matrix.

$$\begin{aligned}&n_{th.n}=17+3,4h_{gr.w.ov}+3,4L_{tl}+3,4D_{y.n}+\\&+0,68h_{gr.w.ov}L_{tl}-0,68h_{gr.w.ov}D_{y.n}+\\&+0,68L_{tl}D_{y.n}+0,14h_{gr.w.ov}L_{tl}\end{aligned} \quad (5)$$

As can be seen from the obtained expression (5), the last coefficient in the polynomial is less than one percent of the value of b_0, and therefore this coefficient can be ignored. Each of the other coefficients has a positive value, is significantly large, and can be said to have an equal effect on the number of openings during the year.

If we analyze the values obtained for the different options given in Table 2, we will see that the number of lightning strikes was the smallest in option 1 and the largest in option 8. From this, we can conclude that in order to minimize the possibility of lightning hitting the line during the year, the height of the line support should be kept as minimal as possible within acceptable limits, and the length of the overhead line should be reduced by choosing the shortest route. In table 3, the values of n_{cal} calculated from formula (1) and the approximation polynomial are shown, along with their difference.

As can be seen from the table, the results are very close, and the difference obtained is less than 1%. Therefore, the determined approximation polynomial can be used to calculate n with high accuracy. It is more convenient to use the obtained formula of the polynomial since it is clearly seen which factor affects how much and in which direction.

In this paper, we also considered other parameters that are affected by the level of lightning resistance.The concept of lightning resistance level is used in calculations to ensure the reliable operation of high-voltage overhead power lines. The level of lightning resistance is evaluated by the maximum amplitude of the lightning current, which causes a breakdown of the insulation of the line, I_o, and the steepness of the voltage wave a ($a=I_o/t_c$, where t_c is the front time of the current wave). The lightning resistance indicator is an indicator of how many years the line is likely to work without a lightning strike.

Table 3. Calculated and experimental values of disconnection during lightning strikes in power lines

№	n_{cal}	$\hat{n}_{polin}$	difference $\left(n_{cal}-\hat{n}_{polin}\right)$
1	8.7	8.84	+0.14
2	13.06	12.92	-0.14
3	13.06	12.92	-0.14
4	19.58	19.72	+0.14
5	13.06	12.92	+0.14
6	19.58	19.72	+0.14
7	19.59	19.72	+0.13
8	29.38	29.24	-0.14

Although lines of 110 kV and above are equipped with a ground wire, a short circuit between the ground wire and the conductor can occur if the magnitude of the voltage wave is large enough during a direct lightning strike. The critical steepness of the voltage wave, which can cause a breakdown between the ground wire and the conductor (in wet conditions), is determined using the following expression [19, 20-21].

Critical steepness of the voltage wave for breakdown between the phase and ground wire

$$a_{c.s}=\frac{2\cdot v\cdot l_{gr.v-c}\cdot E_d}{W_{gr.v}\cdot l_{sl}\cdot\left(1-k\right)} \quad (6)$$

where $W_{gr.v}$ ground wire wave resistance, Ohm; v-wave speed, v=250 m/mk.sec; k – coefficient of electromagnetic coupling, k=0.23; E_d - discharge intensity valuesi, E_d=750kV/m; l_{sl}–span length, l_{sl}=90m; $l_{gr.v-c}$–distance between ground wires and conductor in the middle of the span, $l_{gr.v-c}$= 2m, protective angle α = 25 and $W_{gr.v}$=507.6 Ohm making the appropriate calculations and we determine that, $a_{c.s}$=23.56 kA/mk.sec.

To determine the parameter that most influences the critical steepness of the stress wave and causes breakdown, the method of full factorial planning of the experiment was used here, the results of which are shown in Table 4.

Table 4. Matrix of parameters affecting the critical steepness of the voltage wave

Experiment number №	a	$a_{c.s}$= 23.56		$l_{gr.v\text{-}c}$=2.21		l_{sl}=90		$W_{gr.v}$= 507.6		Z_1 Z_2	Z_1 Z_3	Z_2 Z_3	Z_1 Z_2 Z_3
		Z_0		Z_1		Z_2		Z_3					
1	29.10	23.56	+	1.77	-	72	-	406.08	-	+	+	+	-
2	42.02	23.56	+	2.65	+	72	-	406.08	-	-	-	+	+
3	18.71	23.56	+	1.77	-	108	+	406.08	-	-	+	-	+
4	29.01	23.56	+	2.65	-	108	+	406.08	-	+	-	-	-
5	18.71	23.56	+	1.77	-	72	-	609.12	+	+	-	-	+
6	29.01	23.56	+	2.65	+	72	-	609.12	+	-	+	-	-
7	12.47	23.56	+	1.77	-	108	+	609.12	+	-	-	+	-
8	18.71	23.56	+	2.65	+	108	+	609.12	+	+	+	+	+

The approximation polynomial for determining the lightning resistance level of an overhead power line will be as follows:

$$\begin{aligned} a = 24,71 + 4,97 l_{gr.-c} - 4,99 l_{sl} - 4,99 W_{gr.v} - \\ -0,835 l_{gr.-c} l_{sl} - 0,835 l_{gr.v-c} W_{gr.v} + 0,857 l_{sl} W_{gr.v} - \\ -0,18 l_{gr.v-c} l_{sl} W_{gr.v} \end{aligned} \tag{7}$$

As can be seen from equation (7), the values of the coefficients are quite large and significantly affect the number of lightning strikes. When we compare the coefficients (4.97$l_{gr.v\text{-}c}$; 4.992l_{sl}; 4.99$Z_{gr.v\text{-}c}$), we see that they are equal or very little different. As can be seen from the obtained expression (7), the last coefficient in the polynomial is less than one percent of the value of b_o, and therefore this coefficient can be ignored.

If we analyze the values obtained from the calculation for different options in Table 3, we will see that the critical steepness of the stress wave is the largest in the 2nd option and the smallest in the 7th option. From a comparative analysis of the parameters, it can be concluded that in order to increase the level of resistance of overhead power lines to lightning surges, the distance between the ground wire and the conductor should be taken as minimal within acceptable limits and the span should be at the maximum distance, taking into account the terrain and the dimensions of the supports.

Table 5 shows the values of $\hat{a}_{cal}$ calculated by formula (6) and approximation polynomial (7) and their differences.

Table 5. Calculated and experimental values of the critical steepness of the voltage wave

Experiment number №	a_{cal}	$\hat{a}_{polin}$	Difference $\left(n_{cal} - \hat{a}_{polin}\right)$
1	29.1	28.9	+ 0.12
2	42.02	40.5	+ 1.52
3	18.71	18.9	-0.19
4	29.01	28.9	0.11
5	18.71	18.9	-0.19
6	29.01	28.8	0.21
7	12.47	12.27	0.2
8	18.71	18.87	-0.16

As can be seen from Table 5, the results are very close, and the obtained difference is less than 1%. The specified approximation polynomial can be used to calculate a with high accuracy. From the obtained expression of the polynomial, it is clear which factor affects it to what extent and in what direction, and therefore it is appropriate to use this formula.

Based on the analysis of the results obtained from the above reports, it can be noted that in order to increase the resistance, it is necessary to reduce the height of the supports and minimize the distance between the ground wire and the conductor (α-protection angle) of overhead power lines from disconnection due to lightning. However, from the point of view of operational safety, these parameters cannot be taken below the permissible limit specified in the relevant standards. Therefore, in the presented work, the issue of increasing the efficiency of the ground wire was also considered. It is proposed to solve the problem of high-voltage lines by winding elements of a metal wire in a V-shaped configuration, located at an angle of 45°, along the entire length of the protective cable on a plane perpendicular to the earth's surface, at an equal distance from each other [22].

Increasing the efficiency of the ground wire

As the cloud-to-ground lightning channel approaches the overhead line, there is always a chance that the lightning will bypass the ground wire and strike the live wire. The installation of V-shaped metal elements on the surface of the ground wire increases the inhomogeneity of the electric field and reduces the distance between the ground wire and the lightning channel; due to this, the probability of the lightning channel bypassing the ground wire and striking the conductor is sharply reduced. Such conditions occur over the entire surface of the ground wire, which increases the efficiency of conductor protection by ground wires.

To implement the proposed method of lightning protection of a high-voltage overhead power line, along the entire length of the ground wire, V-shaped elements made of steel wire with a diameter of 1-2 mm (Fig. 2 (1)) are placed at certain distances (for example, 50-100 cm) from each other (Fig. 2 (2)) and fixed by winding so that the free ends are at an angle of 45° in a plane perpendicular to the surface of the earth. Increases in additional lightning protection zones from the length of the V-shaped wire are shown in Fig. 3. If the angle between the ends of the elements is less than the selected value, this will reduce the protection zone, and as a result, the probability of a lightning strike bypassing a protective wire and falling into a current-carrying wire will remain approximately at the same level. If the angle is greater than the selected value, then during lightning processes the resulting inhomogeneous field will shift towards the current-carrying wires and the efficiency of lightning protection of the current-carrying wires will decrease.

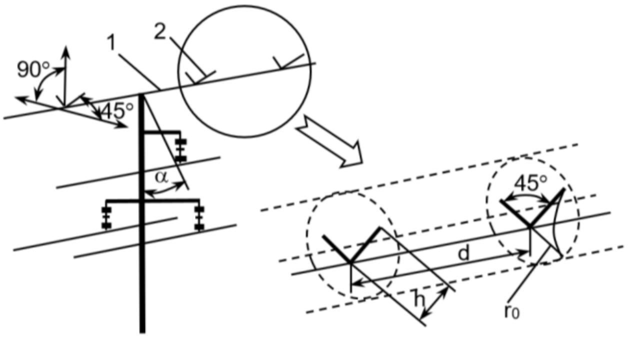

Fig. 2 Location of V-shaped elements on the surface of the ground wire

As is known, the security zone of a single lightning rod can be determined by the expression $r_o = 1.5h$ [23]. Here, *h* is the length of the rod, and r_o is the radius of the protective cone. The zone of additional protection obtained from the calculation by placing the rods at different distances (*d*) along the cable surface (Fig. 1) is given in Table 6. The dependence of the zone of additional protection on the rope on the length of the V-shaped rods (the distance between the rods, *d* = 100 cm) is shown in fig. 3.

Table 6. The protection zone between the "V" shaped rods

The length of the rod, *h*, *sm*	The radius of the protection cone, r_o, sm	An additional zone protected between the "V" rods, %
10	15	30
20	30	60
30	45	90
40	60	120

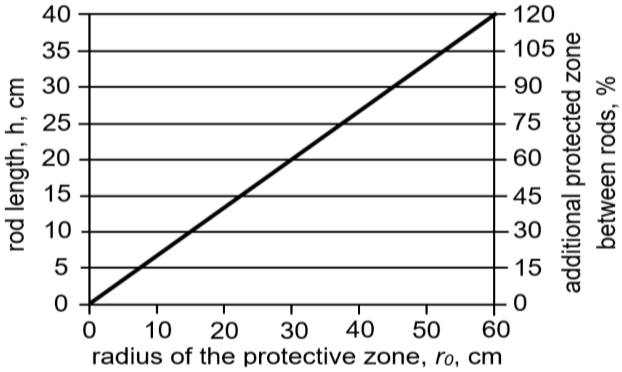

Fig. 3 Dependence of the zone of additional protection of the ground wire on the length of the V-shaped rods

As can be seen from Table 6 and the diagrams in Fig. 3, by changing the distance between the V-shaped rods and increasing their length, we increase the coverage of the protection zone along the surface of the ground wire. Based on the dependence in Fig. 3, it can be concluded that with the length of the rods "V" of 35 cm, the protection zone of the ground wire is additionally expanded over the entire surface with a radius of 55 cm, which significantly reduces the likelihood of a direct lightning strike into the phase conductor.

Thus, the placement of V-shaped metal rods on the ground wire increases the overall protective zone of the lightning rod. The strengthening of the field inhomogeneity occurs not at one point but over the entire surface of the lightning rod, which increases the protection efficiency of current-carrying wires with ground wires. It can also be noted that in places where overhead lines are more affected by lightning, it is more expedient to place such ground wires, and the use of such elements can successfully replace line surge arresters. In addition, a simpler and cheaper proposed design indicates its economic efficiency.

Conclusions

The analysis was carried out by evaluating the main parameters that affect the resistance of high-voltage overhead power lines to lightning surges, and the parameters that have a greater impact on reliability were determined. As such parameters, the height of the towers, the distance between the ground wire and the phase wire, and the length of the main power line were determined. Therefore, in order to reduce the likelihood of direct lightning striking overhead power lines, the height of the towers should be reduced in accordance with the standards, and the distance between the ground wire and the phase conductor should be brought to a minimum within the permissible range. The length of the span should be at the maximum distance, taking into account the terrain and the dimensions of the towers, and when choosing the route, it should be ensured that the total length of the overhead power line is at a minimum distance. In order to further improve the reliability of the overhead power transmission line, it is proposed to wind metal rods in the shape of the letter "V" around the ground wire at certain intervals, which increases the protection zone of the ground wire. At the same time, the field heterogeneity between the lightning and the ground wire increases, the possibility of lightning bypassing the ground wire and making a direct strike with the phase line decreases, and the lightning protection effect of the ground wire as a whole increases.

Authors. *Ahmadov Elbrus Nasi. Associate Professor, Candidate of Physical and Mathematical Sciences. Head of the Department of Electromechanics Azerbaijan State University of Oil and Industry. Baku city, Azadlyg avenue 20, E-mail: elbrusahmed@gmail.com .*

Rzayeva Sona Vagif. Head of the Laboratory of the Department of Electromechanics of the Azerbaijan State University of Oil and Industry. Baku city, Azadlyg avenue 20, E-mail: soni_76@mail.ru

Ganiyeva Nigar Akif. Laboratory assistant at the Department of Electromechanics of the Azerbaijan State University of Oil and Industry. Baku city, Azadlyg avenue 20, E-mail: nigar.atakisiyeva75@mail.ru

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