Probability estimation of lightning attachment to conductors of 110-220 kV overhead power lines without shielding wires due to the instantaneous phase voltage

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***Abstract*— Calculation results of lightning attachment probability to phases of 110-220 kV overhead lines without shielding wires depending on polarity of voltage instantaneous value are provided. The criterion of steady evolution of an upward connecting leader from the conductor is used as the criterion of stroke attachment to one or another phase. For a 220 kV overhead line with horizontal arrangement of conductors without a shielding wire the probability that negatively charged lightning will strike positively charged phase is about three times as high as that for negatively charged one.**

The calculation results are in good agreement with data recorded for a 220 kV overhead line in pilot operation.

Keywords — attachment, overhead lines, upward leader, voltage polarity.

I. Introduction

Recently there have been proposals on implementing multi-chamber insulator-arresters (MCIA) for lightning protection of high-voltage overhead lines [1]. They can be used for overhead lines both with and without shielding wires. In the latter case MCIA operating conditions are more severe since in case of a direct lightning stroke to the conductor the lightning overvoltage impulse current, which can reach tens of kA, flows through a multi-chamber system (MCS). Besides, network follow current i_f tends to flow along the discharge channel formed by impulse current i_i and total discharge current is:

$$i_d = i_i + i_f. \tag{1}$$

Lightning can strike a conductor any time. At that, the voltage instantaneous value on the conductor can be of the same polarity as that of lightning, but it can also be the opposite one.

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In case lightning and conductor voltages are of different polarities, currents i_i and i_f flow adversely and the total discharge current i_d passes through zero.

In case of the same polarity arc-quenching conditions are more severe than in case of different polarities as currents i_i and i_f flow in one direction, and in case of arc non-quenching (for example, on a common string of insulators) total discharge current i_d does not pass through zero.

In order to conduct proper tests of MCIA designed for installation on overhead lines without shielding wires it is desirable to know the ratio of polarities of lightning and overhead line conductor during direct lightning stroke (DLS).

Impact of operating voltage on the shielding failure probability is investigated in [2, 3]. It is shown that in presence of a shielding wire the effect of operating voltage impact significantly reveals itself for extra-high voltage lines (500 kV and above). It is insignificant for lines of lower rating.

However, in absence of a shielding wire, the situation can greatly change as different overhead line phases are approximately in the same conditions and impact of conductor voltage instantaneous values can be significant for lightning attachment.

The decisive factor for conductor stroke attachment is evolution from it of a stable upward connecting leader. Conditions of its evolution are similar to those of a leader in long air gaps under impact of impulses of switching overvoltages with 1-3 msec front length [4].

Let's explain this assertion in detail with the use of simple calculation. As it is common in many similar calculations, a lightning can be represented, in a simplified form, as a vertically arranged, rather long equivalent conducting cylinder (see Fig. 1).

The linear charge can correlate with lightning current according to the equation [6]:

$$q_l = \sqrt{\frac{I_l}{1{,}56}} \times 100, \tag{2}$$

where I_l is lightning current, kA; q_l is the linear charge, μC/m.

The calculation was conducted for the average lightning current value I_l = 30 kA. At that, the charge calculated based on (2) equals q_0=440 μC/m.

In calculations based on the method of equivalent charges the lightning channel was represented as a vertical cylinder-shaped conductor with length L=5000m.

The radius of the cylinder representing lighting channel was calculated based on the following formula

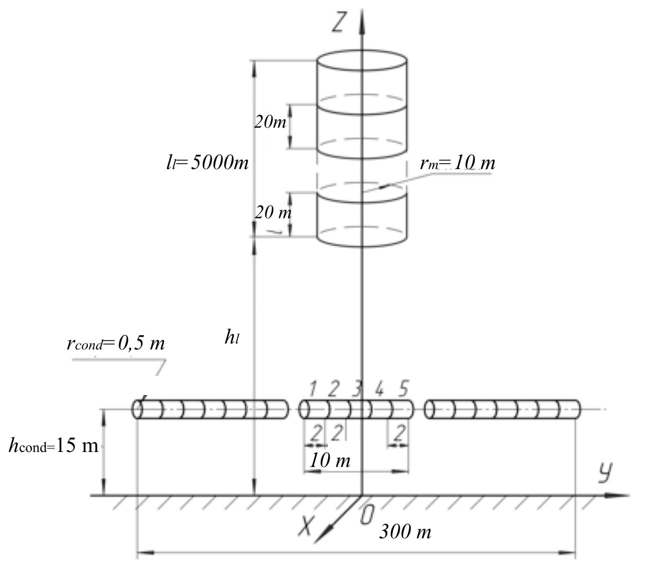

Fig. 1. Calculation model for lightning above OHL conductor.

$$r_l = \frac{q_0}{2\pi\varepsilon_0 E_{\text{стр}}} = \frac{440\times10^{-6}}{2\times3{,}14\times8{,}85\times10^{-12}\times0{,}8\times10^{6}} \approx 10\text{м}, \qquad (3)$$

where E_{str} =0.8 MV/m is the electric field strength for streamer zone of negatively charged lightning channel;

Lightning height (distance between the lower end of the cylinder and ground) varied from h_l = 200 to 50 m. Cylinder potential was accepted as 20 MV [4].

A single transmission line conductor was represented (with account for its corona) by a section of cylinder with radius of 0.5 m and length 300 m, arranged in parallel to ground surface at height h_{cond} = 15 m. To account for irregularity of charge distribution along the specified cylinder, it was divided into sections as long as 2 m. Potential of the conductor-representing cylinder was accepted as zero.

Fig. 2 shows results of calculating electric field strength distribution along the conductor depending on the horizontal distance from the vertical axis along which the lightning-representing cylinder was arranged. Certainly, the lower lightning is above the ground, the higher electric strength of the conductor is. The strength is maximum at the central part of the conductor, and it decreases as the distance to the center increases.

At the same time it is clear that with the specified lightning height above ground h_l electric field strength remains almost stable on the surface of the cylinder (representing a conductor surrounded with space charge) at the distance to the vertical axis of up to 5 m. Moreover, this is true with lightning height above ground decreasing to 50 m, i.e. almost at all lightning orientation heights.

This means that the pattern of electric field close to the conductor at the central section with length of about 10m is parallel-plane. It should be noted that for the purposes of modeling electric field at the central conductor section directly under a lightning the position of the lightning (vertical or horizontal) is of no fundamental importance. In fact, what matters is values of charges induced by lightning at different OHL phases

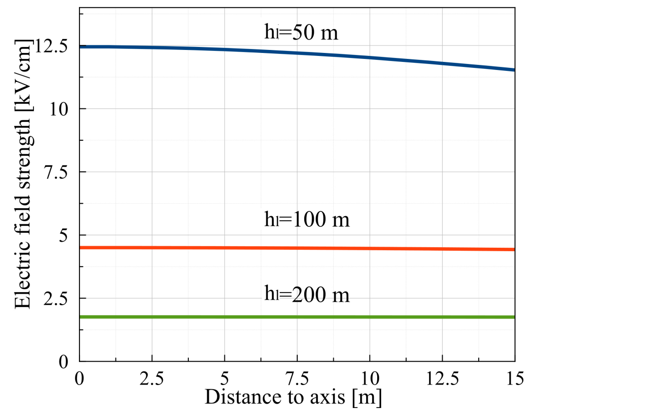

Fig. 2. Dependences of electric field strength at horizontal cylinder surface on distance to the vertical axis for different heights of the cylinder (lightning) lower end above ground surface h_l.

Therefore, in order to analyze conditions of upward connecting leader evolution from the conductor one can use results of analyses of electric strength of long air gaps between parallel conductors.

Reference [5] suggests a method of calculating the electric strength of long air gaps between parallel conductors under application of impulses of switching overvoltages. This method can also be used to assess the probability of upward connecting leader evolution from one or another overhead line phase.

II. METHOD FOR CALCULATING 50% BREAKDOWN VOLTAGES

The main principles of the method are shown in Fig. 3. When conductors are stressed by impulses of switching overvoltages streamer zones are formed near conductors. Electric field strengths along streamer zones are constant. Their values are 4.5 kV/cm for positive zone and 7 kV/cm for negative one. In case voltage applied to conductors increases, so do lengths of zones.

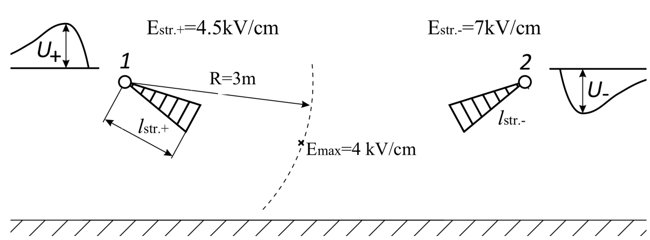

Fig. 3. For calculating 50% discharge voltages between parallel conductors:
1 – positively charged conductor with streamer zone length $l_{str.+}$;
2 – the same for negative polarity $l_{str.-}$.

Simultaneously, the average field strength at the distance of R=3 m from positively charged conductor increases, too. In one of the directions the average electric field strength has its max. value. In case of reaching the value of E_{max}=4 kV/cm in this direction a leader evolves from the positively charged conductor towards the negatively charged conductor. With 50% probability this leader will lead to the breakdown of the air gap between the conductors, i.e. this will occur in case of 50 % discharge voltage.

Following determination of lengths of streamer zones and their corresponding charges, potentials of conductors U_+ and U_-, as well as $U_{50\%} = U_+ - U_-$ are calculated.

III. CALCULATING LIGHTNING STROKE ATTACHMENT TO OVERHEAD LINE PHASES

More than 90% of descending lightnings are known to have negative polarity. Therefore, further on we will consider negatively charged lightning.

Lightning in its leader stage is a conducting channel surrounded with space charge. Streamers evolve from lightning leader head, forming a streamer zone filled with space charge. With negatively charged lightning approaching the overhead line a positive charge is induced on conductors, a strong electric field forms, positive polarity streamer zones evolve, followed by upward leaders. The longest upward leader meets the lightning descending leader, thus determining the place for lightning stroke.

In order to assess the lightning stroke attachment to one or another phase it is suggested that one should use the method similar to the one described in Section II. To determine the conductor from which the upward leader is to evolve earliest and, correspondingly, the one lightning is to strike, it is recommended to significantly simplify electric field calculations:

1. 3D lightning and overhead line system is replaced by a parallel-plane system of conductors with streamer zones;
2. Dynamically changing picture of evolution of lightning and upward leaders is replaced by a series of electrostatic field calculations based on method of equivalent charges.

The method of assessing stroke attachment to conductors is shown in Fig. 4. Conductors and lightning channel are taken as strictly parallel to the earth surface, which is also taken as an ideal conducting plane. Charges are considered to be uniformly distributed along conductors and streamer zones.

Streamer zones occupied by space charge are seen as infinitely long triangular prisms parallel to conductors (see Fig. 4). Space charge zones are broken into m of parallelepipeds. Space charge is accepted to be equally distributed in them. Charges on surfaces of conductors and lightning channel are replaced with linear charges located along their axes.

Reference points are located on surface of each conductor, as well as on borders of each elementary parallelepiped of space charge. The number of reference points equals the number of unknown elementary charges $N=n(m+1)$, where $n = n_{cond.} + 1$ – number of overhead line conductors plus lightning.

The flow chart of the calculation method is shown in Fig. 5. Initially coordinates of overhead line conductors,

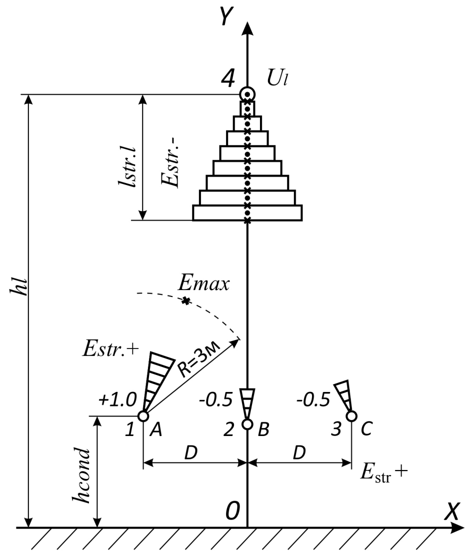

Fig. 4. Diagram for assessing stroke attachment to conductors.

conductor radius and potentials of conductors equal to instantaneous values of phase voltage are given. For instance (see Fig. 4), let's take the instance when instantaneous value of phase A voltage (conductor №1) is max. and has positive polarity, i.e. U_A=+1,0 p.u. At that, voltages on phase B (conductor №2) and phase C (conductor №3) equal U_B=-0.5 and U_C=-0.5 p.u. Per-unit values are used for clarity, Fig. 4. Calculations use actual values of potentials.

Lightning channel coordinates are given as well. Fig. 4 shows an example of lightning aligning the center of overhead line at height h_l.

Initial approximate lengths of streamer zones of overhead line conductors and lightning are entered, for example: $l_{str.1}$=1.0 m; $l_{str.2}$=0.5 m; $l_{str.3}$=0.5 m and $l_{str.l}$=20m.

Position of equivalent charges and reference points is calculated.

Electric field strength values in reference points are assigned. In positively charged streamer zones of conductors electric field strength value in all reference points is given equal $E_{str.+}$=4.5 kV/cm, while in negatively charged streamer zone of lightning $E_{str.-}$=7 kV/cm.

A system of linear equations is formed

$$[b]\cdot[q]=[E], \qquad (4)$$

where $[b]$ is a matrix of electric field coefficients in equations $E_i = b_{i,j} \cdot q_j$; E_i is electric field strength in point i of equivalent charge q_j with number j, (i, j = 1,2,…,N).

As a result of solving the system (4), equivalent charges $[q]$ are determined and potentials of all conductors φ_i (i =1,2,3) are calculated. Formulae for calculating $b_{i,j}$ and φ_i are shown in [5].

Since lengths of streamer zones were arbitrary, calculated potentials of conductors φ_i differ from the given ones U_i. Lengths of zones l_i should be such so that calculated potentials of conductors equal the given

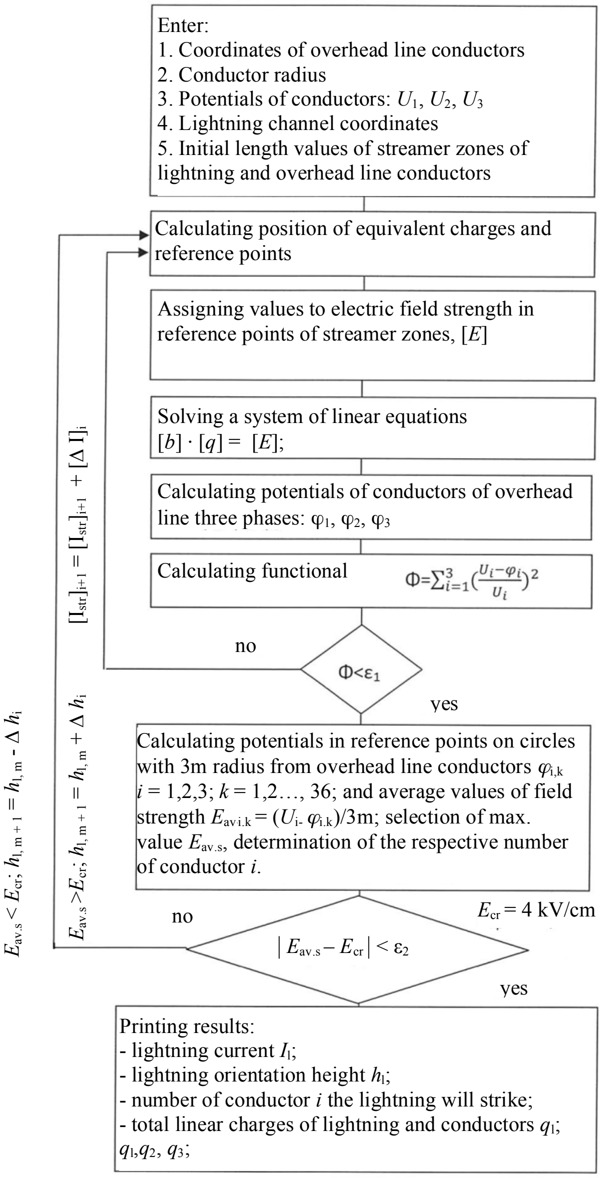

Fig. 5. Flow chart for calculating lightning stroke attachment to conductors.

voltages of conductors. This condition is met if functional (5), depending on lengths of streamer zones, takes the value close to zero

$$\Phi(l_1, l_2, l_3)=\sum_{i=1}^{3}\left(\frac{U_i-\varphi_i}{U_i}\right)^2. \quad (5)$$

Required lengths of zones l_1, l_2, l_3 are determined iteratively. If for any k iteration Φ value exceeds the allowed error ε_1, values of lengths of streamer zones are adjusted (6) and the cycle of functional calculation repeats itself (see Fig. 5). If $\Phi<\varepsilon_1$, one moves to the next calculation stage.

$$[l_{str}]_{k+1}=[l_{str}]_k+[\Delta l]_k \quad (6)$$

Potentials in reference points on circles with 3m radius from overhead line conductors $\varphi_{i,k}$ i=1,2,3; k=1,2…, 36; and average values of electric field strength are calculated

$$E_{av\cdot i,k}=(U_i- \varphi_{i,k})/3\text{m}; \quad (7)$$

Then, max. value of $E_{av.s}$ is chosen and the corresponding number of conductor i is determined.

If for m iteration the calculated value of max. average field strength $E_{av.s}$ differs from the given critical value E_{cr} = 4 kV/cm by more than the given calculation error ε_2, then the above-the-ground lightning height h_l is adjusted and the calculation cycle is repeated. If $E_{av.s}>E_{cr}$, lightning height value for next m+1 iteration increases $h_{l.,m+1}= h_{l.,m} + \Delta h_i$, and if $E_{av.s}<E_{cr}$, it decreases $h_{l.,m+1}= h_{l.,m} - \Delta h_i$.

$$\text{If} \quad |E_{av.s}-E_{cr}|<\varepsilon_2, \quad (8)$$

lightning current I_l is assessed based on total linear lightning charge value q_l (2)

$$I_l = 1{,}56\left(\frac{q_L}{100}\right)^2, \quad (9)$$

where I_l is lightning current, kA; q_l is the linear charge, μC/m.

Here the calculations come to an end. The results are printed:
- lightning current I_l ;
- lightning orientation height h_l;
- number of conductor i lightning will strike and its polarity;
- total linear charges of lightning and conductors q_l; q_1, q_2,q_3.

IV. CALCULATION RESULTS

A. *single-circuit 220 kV OHL*

Instantaneous values of voltage on conductors of a three-phase overhead line are determined by means of the formulae:

$$U_A=U_l\cdot\sin(\alpha);$$
$$U_B=U_{Ml}\cdot\sin(\alpha\text{-}120^o);$$
$$U_C=U_l\cdot\sin(\alpha\text{-}240^o), \quad (10)$$

where α is electric angle in degrees.

Lightning can strike a conductor anytime, i.e. at any value of α angle. At that, the ratio of instantaneous values of voltage on phases can be different. For the sake of analyzing the lightning stroke attachment to one or another phase the whole voltage cycle, to which α angle variations from 0 to 360 ^{o} correspond, is divided into six ranges. Calculations were conducted with average instantaneous values of phase voltages for each range (see Table 1).

Lightning position in relation to an overhead line can also be different (see Fig. 6). For calculations, the overhead line was located symmetrically to the axis of ordinates.

TABLE I

RESULTS OF CALCULATIONS FOR A SINGLE-CIRCUIT OVERHEAD LINE 220 KV PARAMETERS

№	α, degrees range average value	phase voltages, p.u. U_A U_B U_C	x_{left}, m	x_{right}, m	b, m	x_1, m	x_2, m	b_-, m	b_+, m	$P_{-/-}$	$P_{-/+}$
1	0-60 30	0.5 -1 0.5 ● ● ●	-50	50	100	-	-	0	100	0	100
2	60-120 90	1 -0.5 -0.5 ● ● ●	-55	40	95	10	40	30	65	0.32	0.68
3	120-180 150	0.5 0.5 -1 ● ● ●	-50	40	90	15	40	25	65	0.28	0.72
4	180-240 210	-0.5 1 -0.5 ● ● ●	-40	40	80	-40* 20	-20* 40	20* +20	40	0.50	0.50
5	240-300 270	-1 0.5 0.5 ● ● ●	-40	50	90	-40	-25	15	75	0.17	0.83
6	300-360 330	-0.5 0.5 1 ● ● ●	-40	55	95	-40	-15	25	70	0.26	0.74

Note: x_{left} is coordinate of the left border of lightning capture zone; x_{right} is coordinate of the right border of lightning capture zone; $b_\Sigma = x_{right} - x_{left}$ is the capture zone width; x_1 is coordinate of the left border of the zone of lightning stroke in negative voltage phase; x_2 is coordinate of the right border of the zone of lightning stroke in negative voltage phase; $b_- = x_2 - x_1$ is width of the zone from which lightning strikes phase with negative voltage polarity; b_+ is width of the zone from which lightning strikes phase with positive voltage polarity; $P_{-/-}$ is the probability of negatively charged lightning stroke in negative polarity phase; $P_{-/+}$ is the probability of negatively charged lightning stroke in positive polarity phase; $P_{-/-,av}$=0.25 and $P_{-/+,av}$=0.75 are average values; *) the given variant has two b- zones.

The initial lightning channel position was situated at the height of 100 m above the ground, coordinates along the axis of abscissas varied from -100 to +100 meters. Calculations were conducted for lightning current 30 kA, i.e. for mathematical expectation of its value [7]. At that, according to calculations, length of lightning streamer zone is about 20 m.

The design of 220 kV overhead line is schematically shown in Fig. 4. The distance between the phases is 5 m; equivalent height of suspension of conductors is 10 m; no shielding wire.

Calculations were conducted in the following way. Lightning channel coordinates are given (i. e. of a metal cylinder which simulates it), for example, x_l=-100 m; y_l=100 m, along with all other initial data (see Fig. 6).

The calculations are carried out with the use of methods described in Section III. It turns out that there are no conditions for evolution of a stable upward leader at any lightning height above the ground. It means that lightning will not strike the overhead line. Then, the horizontal lightning-overhead line distance is reduced by some value, for example, by 5 m, and calculations are repeated.

Fig. 6 shows a case when voltage instantaneous value at left phase A (conductor № 1) equals U_A= +1 p.u. (180 kV); that at the middle phase B (conductor № 2) U_B= -0.5 p.u. (-90 kV); and that at the right phase C (conductor № 3) U_C= -0.5 p.u. (-90 kV). Table 2 lists basic calculation parameters for this case.

As a result of a series of calculations, one determines the border of zone x_{left}, in which lightning starts to orient at the overhead line (left border of the lightning capture zone), in this case – at positively charged phase A, close to which conditions of steady evolution of an upward leader are met (see Section III).

Then lightning position is further shifted to the right and border x_1, to the right of which lightning starts to strike negatively charged phase C, is determined.

TABLE II

BASIC CALCULATION PARAMETERS

Object	Streamer zone area, m	Potential, MV	Total linear charge, μC/m
Phase A	2,26	0.18	22.1
Phase B	0,73	-0.09	8.13
Phase C	1,04	-0.09	11.3
Lightning	22,0	-28.7	-440

Note. Lightning orientation height 100 m.

The right border of lightning capture zone x_{right} is determined in the same way

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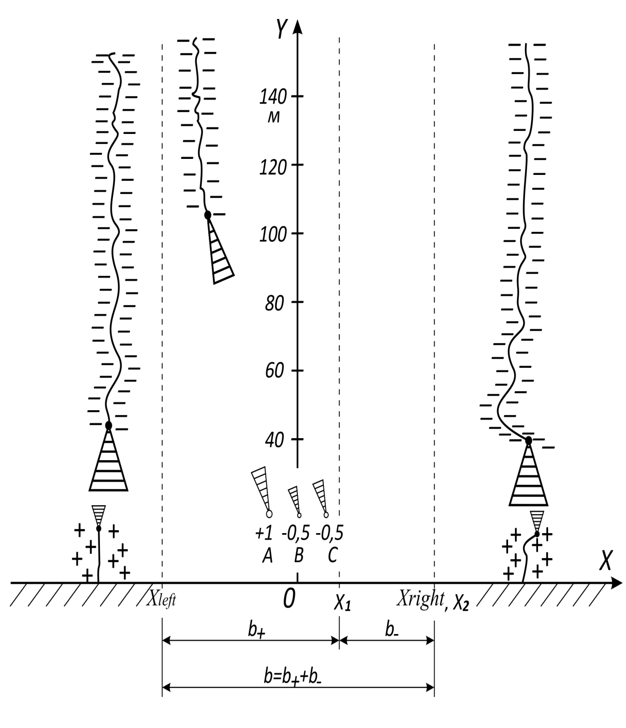

Fig. 6. Illustration for assessing the lightning stroke attachment to overhead line conductors

In the given case, the width of the zone in which negatively charged lightning will strike positively charged phase of the overhead line, is $b_+ = x_1 - x_{left}$; Similarly, for the zone in which lightning strikes negatively charged phase, $b_- = x_2 - x_1$. The width of the total capture zone is $b = b_+ + b_-$.

In case lightning struck the line, the probability that negatively charged lightning struck positively charged phase, can be assessed as $P_{-/+} = b_+/b$. Similarly, for the probability of stroke in negatively charged phase, $P_{-/-} = b_-/b$.

As one can see in Table 1, probabilities $P_{-/+}$ and $P_{-/-}$ greatly depend on the instance of lightning strike (i.e. on α). For example, at $\alpha = 30^0$ (variant №1) $P_{-/+} = 1$ and $P_{-/-}=0$, while at $\alpha = 210^0$ (variant №4) $P_{-/+} = P_{-/-} = 0.5$. Their average values make up $P_{-/-.av}=0.26$ and $P_{-/+,av}=0.72$, i.e. the probability that negatively charged lightning will strike positively charged phase is about three times as high as that for the negative one.

In 2011-2012 a system of recording overhead line outages was in pilot operation on 220 kV overhead line in South Russia. The system is based on taking oscillograms of voltages and currents in overhead line phases by means of devices installed at sending and receiving substations (developed by Siberian Electric Power Research Institute). As a result of processing measurement data, the general distribution of instances of lightning strokes to overhead line phases by voltage cycle was obtained (see Fig. 7).

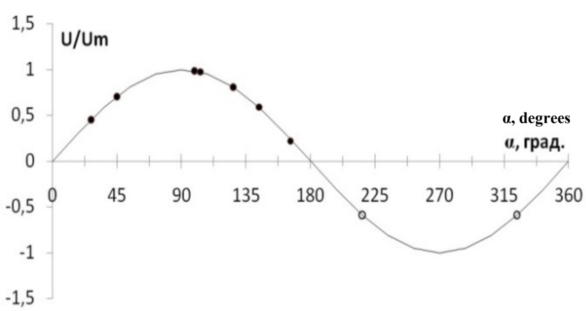

Fig. 7. Distribution of instances of phase lightning strokes for a 220 kV overhead line by voltage cycle:
● – lightning stroke in positive half-cycle of voltage; ○ – the same, but in negative half-cycle.

In total, there were recorded 9 strokes of negatively charged lightning in conductors: 7 strokes in positive half-cycle and 2 – in negative one. Thus, recorded stroke rates $F_{-/+} = 7/9 = 0.78$ and $F_{-/-} = 2/9 = 0{,}22$ are in good agreement with calculated probabilities of stroke attachments to phases $P_{-/+,av}=0.75$ and $P_{-/-.av}=0.25$.

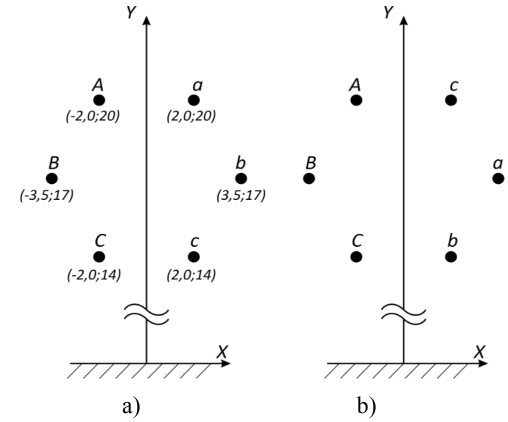

Fig. 8 Diagram of arrangement of 110 kV double-circuit overhead line conductors: a) conventional one; b) phases of circuits at the same level are different. Coordinates of conductors are given in brackets.

B. Double-circuit 110 kV OHL

Fig. 8a shows a diagram of conventional arrangement of phases of a 110 kV double-circuit overhead line with equivalent heights of conductor suspension. In this case conductors suspended at the same level above the ground have similar voltage phases: (*A*,*a*), (*B*,*b*), (*C*,*c*).

According to the calculations conducted with the above described method, lightning always strikes upper conductors (i.e. phases *A*,*a*, see Fig. 8a), irrespective of instantaneous voltage polarity of conductors. Since durations of positive and negative half-cycles of voltage are the same, probabilities of negatively charged lightning strokes in positively or negatively charged conductors are also the same $P_{-/+} = P_{-/-} = 0.5$.

If the phase sequence of overhead line circuits is changed in accordance with Fig. 8b, i.e. in accordance with the diagram: (*A*,*c*), (*B*,*a*), (*C*,*b*), ratio of $P_{-/+}$ and $P_{-/-}$ changes significantly. Table 3 lists calculation results for a 110 kV double-circuit overhead line, with phase sequence according to the diagram of Fig. 8b. The calculations took into account only conductors suspended at two upper cross-arms since lower conductors have almost no impact on lightning orientation.

According to Table 3, for the phase sequence shown in Fig. 8b, the probability that negatively charged lightning will strike positively charged phase is almost four times as high as that for the negatively charged one. Conditions of arc-quenching by MCIA multi-chamber systems with different polarities of lightning and network are significantly easier than with the same polarity. Therefore, in order to increase effectiveness of MCIA operation it is reasonable to arrange conductors of different phases on upper cross-arms (see Fig. 8b).

TABLE III

RESULTS OF CALCULATIONS FOR A DOUBLE-CIRCUIT OVERHEAD LINE 110 KV PARAMETERS

№	α, degrees <u>range</u> average value	Phase voltages, p.u.	x_{left}, m	x_{right}, m	b, м	x_1, m	x_2, m	b_-, m	b_+, m	$P_{-/-}$	$P_{-/+}$
1	<u>0-60</u> 30	0,5●$_{Ac}$●0,5 -1,0●$_{Ba}$●0,5	-60	60	120	-	-	0	120	0	1.0
2	<u>60-120</u> 90	1,0●$_{Ac}$●-0,5 -0,5●$_{Ba}$●1,0	-60	55	115	30	55	25	90	0.22	0.78
3	<u>120-180</u> 150	0,5●$_{Ac}$●-1,0 0,5●$_{Ba}$●0,5	-60	50	110	25	50	25	85	0.23	0.77
4	<u>180-240</u> 210	-0,5●$_{Ac}$●0,5 1,0●$_{Ba}$●0,5	-55	60	115	-55	-25	30	85	0.26	0.74
5	<u>240-300</u> 270	-1,0●$_{Ac}$●0,5 0,5●$_{Ba}$●-1,0	-55	60	115	-55	-30	25	90	0.22	0.78
6	<u>300-360</u> 330	-0,5●$_{Ac}$●1,0 0,5●$_{Ba}$●-0,5	-55	60	115	-55	-30	25	90	0.22	0.78

<u>Note:</u> see Note to Table 1; $P_{-/-,av}$=0.19 and $P_{-/+,av}$=0.81 are average values.

V. CONCLUSIONS

1. A method to assess impact of voltage instantaneous value of high-voltage overhead line phases on phase lightning stroke attachment is described.
2. For a 220 kV overhead line with horizontal arrangement of conductors without a shielding wire the probability that negatively charged lightning will strike positively charged phase is about three times as high as that for negatively charged one.
3. Calculated results are in good accordance with data of field measurements for a 220 kV overhead line.
4. For a 110 kV double-circuit line probability that negatively charged lightning will strike positively charged phase is almost four times as high as that for negatively charged one.
5. Therefore in order to increase effectiveness of MCIA operation it is reasonable to arrange conductors of different phases on upper cross-arms.
6. For an extra high-voltage overhead lines 330-750 kV without shielding wires one can expect even more significant impact of operating voltage on orientation of lightning stroke to the phase with polarity opposite to that of lightning.

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