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Main aspects influencing the evaluation of atmospheric overvoltages in high-voltage networks

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Abstract. The effectiveness of lightning protection on the power and distribution grid is a significant factor, which influences the power distribution reliability and the failure rate of system elements. As part of this article, a mathematical model will be presented, taking into account selected parameters that affect the assessment of the lightning hazard of an overhead line. The proposed model will consider the location of the object near the line and the adjustment of line conductor overhangs. Moreover, the mentioned mathematical model allows for analyzing the impact of considered parameters on the protection level of the power system, and transient overvoltages that occur in this system. The article contains also a detailed description of an effective and fast method to assess the lightning discharge impact on the power system with insufficient data. The introduced model was tested to verify the correctness of its operation by comparison of calculation results and functional data. High convergence of calculated and functional data and uncomplicated model structure ensure a wide range of applications for the proposed solution to easily prevent emergency situations in the power system. Furthermore, the described model gives the opportunity to assess the reduction of the range of selectivity zone associated with the power line, in conjunction with the impact of constructional peculiarities and a near object.

Key words: overvoltage protection; high-voltage network; reliability of power grids; risk analysis.

1. Introduction

Overvoltages that occur in power and distribution grid have a significant impact on the number of emergency shutdowns of overhead lines. A high factor of a power outage due to lightning has also been reported in some countries [1]. Despite recent progress in the area of overvoltage protection, current statistical data that has been used around the world show that lightning activity remains the dominant factor affecting the overhead failure rate [2–6]. Analyzing the basic causes of failures in power networks based on the data presented in Fig. 1, we see the confirmation of the above statement [7]. Lightning strikes cause failures twice as often as other factors.

Among the factors that influence the line disconnection under the influence of atmospheric surges, the following can be listed: the number of lightning discharges in and around the overhead line, the insulation strength installed on the considered line, the earth resistance of the poles, the presence and location of ground wires and lightning/surge arresters. Matching the strength of the overhead line (and its components as in Fig. 2) to the expected lightning currents plays an important role in the reliability of consumer power supply.

Figure 3 presents information about the impact of the lightning strike to the line on the type of damage of its elements [8]. It can be seen that damage to the insulator chains is the most emergency structural element of the overhead line in the event of a lightning strike. The failure rate of the other elements is about the same.

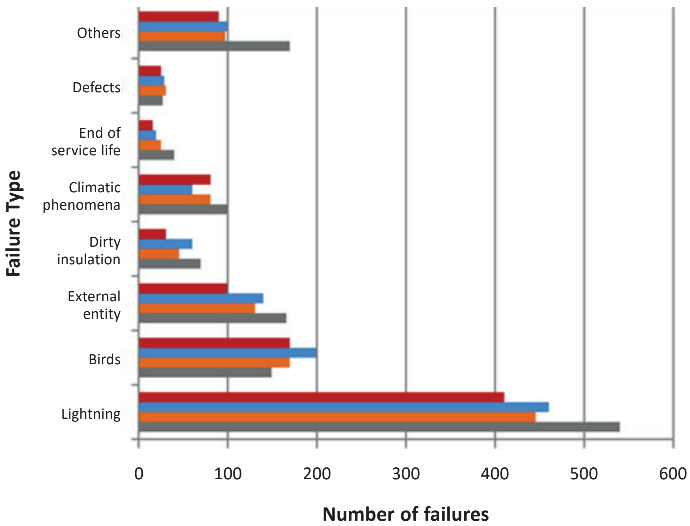

Fig. 1. Statistical data on the failure of the power grid (110–750 kV) in 2014–2017

The analyses can be divided into several categories: theoretical studies based on simplified analytical formulas [3, 5, 9, 10], computer simulations based on the finite element method [11–14]. The results of the analysis of some models indicate that the impact on the level of overvoltages has wire location and grounding parameters [15–17].

Referring to the adopted models of overhead lines, it can be concluded that real terrain parameters can have quite an unde-

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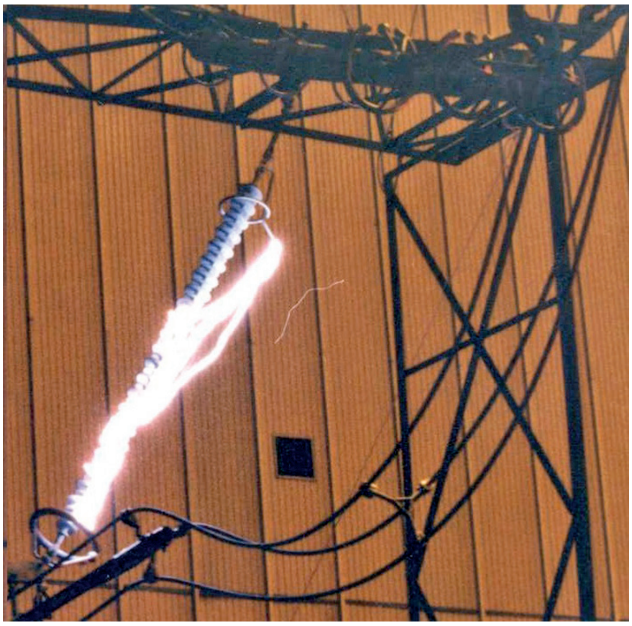

Fig. 2. An example of the overvoltage process on isolator chains

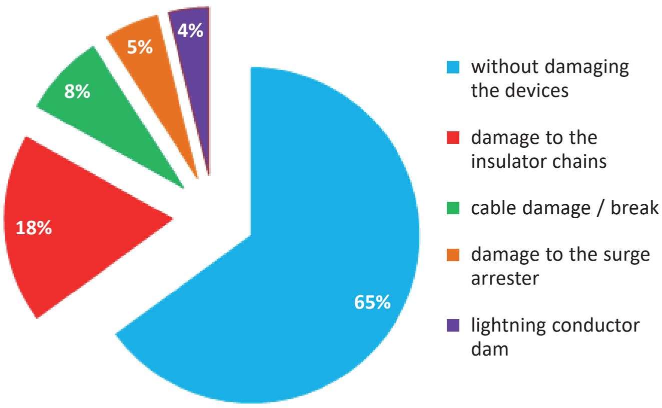

Fig. 3. Information on damage to individual elements of the overhead line as a result of a lightning strike (Number of damages, pcs / year)

sirable impact on the line's exposure to direct lightning strike. The number of lightning strikes in and around the overhead line depends on such factors as: given region (statistical data on the number of storm days in a year) in which the overhead line is located and how the wide route of the line (technological zone of the line, which takes into account the cutting of trees enabling proper operation of the power line) depends on the type of towers (structures designed and adapted in terms of mechanical and electrical strength to route overhead lines taking into account the purpose and type of work in the line) and line voltage level (nominal voltage).

There are also components that are difficult to include in the preliminary analysis. These factors can be referred to: the presence of selected high poles on the route (such as tall lattice towers in woodland), crossing the line over large water reservoirs (what leads to use of very tall towers or pylons), overhead lines crossing with other overhead lines and landforms. Until now, a lot of research has been focused on the study of physical factors and parameters that reveal the impact of lightning on an overhead line [18]. The amplitude of the lightning current flowing through the object, as well as the height at which the place of the lightning strike can be determined, depends on the value of the leader charge. Taking it into account, a relationship between the lightning current and the height mentioned above could be obtained [19]. In addition, an important aspect is the place of lightning in relation to individual structural elements (tower, phase conductor, ground wire, etc.) [20]. There are several options to determine the number of strokes to a span and the contribution of strikes to a tower and a phase conductor. Some of the above possibilities assume that the phase conductor between two towers can be considered as an object protected by these towers [21, 22]. As a result of research on models of high objects, it has been clarified that the lightning channel is not always vertical and the earth is not a suitable conductor [23]. The lightning hazard assessment in the context of lightning polarity was analyzed in [24, 25]. At the same time, the indicator of overhead lines resistance to lightning during the year has different levels of precision.

In order to assess possible adverse effects of lightning strikes on the overhead line, this article assumes the maximum value of induced overvoltages that may occur in the grid that may occur. Due to a large number of parameters and the relative complexity of the simulation of some important aspects, the analysis of the overhead line resistance to lightning takes really a lot of time, therefore, the authors decided to limit the number of analyzed parameters. Aiming to minimize such numerical difficulties, a mathematical model was investigated and developed. In this article, it was decided to focus on developing a model, which takes into account the structural peculiarities of the overhead line and the terrain where this line is located. This approach takes into account the parameter regarding the number of lightning strikes per line per year.Other aspects (including damage to individual line elements as a result of lightning strikes, electric field analysis) are not included because they are subject to analysis of other models [26–31]. The proposed methodology led to the determination of the number of lightning strikes in the analyzed overhead line, but at the same time it is very fast and possible to apply in the case of the minimum amount of data.

2. Assumptions for the mathematical model

The frequency of lightning strikes the line – as already mentioned – depends on the terrain where the line is located. It may have adjacent trees may be located close to the line, as shown in Fig. 4. To develop a mathematical model, the assumption was made that the analyzed line sections have a comparable level of lightning resistance (insulator, tower, ground parameters, etc.) as the line on its entire length. The basis for the assessment of the overvoltage threat in a given area is the knowledge of the expected number of lightning strikes that can hit a specific section of this line during the year. In the line, without considering sag, this number is approximated using the following formula:

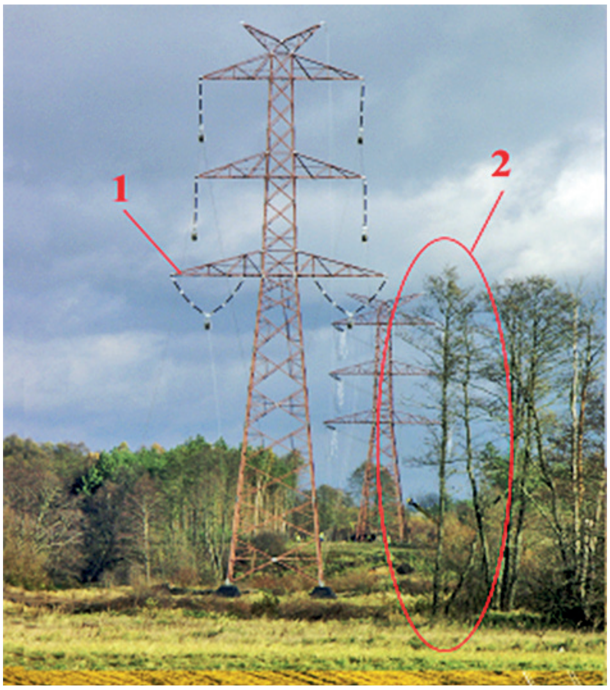

Fig. 4. Example location of trees near the overhead line, assuming $h_d < h_l$

$$N = 2N_d mhb_p 10^{-6}, \tag{1}$$

in which N_d [pcs/year] is the statistical number of cloud-to-ground flash density in a given area, available on the isokeraunic maps, m – the coefficient of lightning attraction range across the line (multiple of its height h [m]). The meaning of other symbols base on the data taken from Fig. 5. The range coefficient for an object height h less than 40 m is from the formula [28]:

$$m = 13.4h^{-0.5}. \tag{2}$$

For the calculation of the number N, the following aspects related to the change of ratio between direct and nearby strikes should be taken into account:

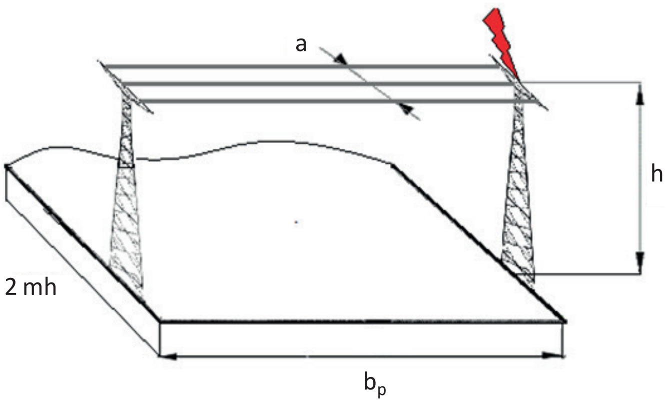

Fig. 5. Span of the line to approximate calculations of the frequency of lightning strikes

Fig. 6. Overhead line span with the sag of the upper phase conductor

1. Conductor sag (Fig. 6)
2. Objects located near the line (Fig. 4).

Due to the need to take into account aspects related to the reduction of the expected number of lightning, a mathematical model for the analyzed cases will be proposed later in the article.

3. The mathematical model considering a sag

Referring to first aspect of two selected above, the influence of sags is presented in Fig. 7, where the k_z coefficient is significantly affected by the reduction of the range of the effect zone of lightning surges through the line, which can be determined from the formula:

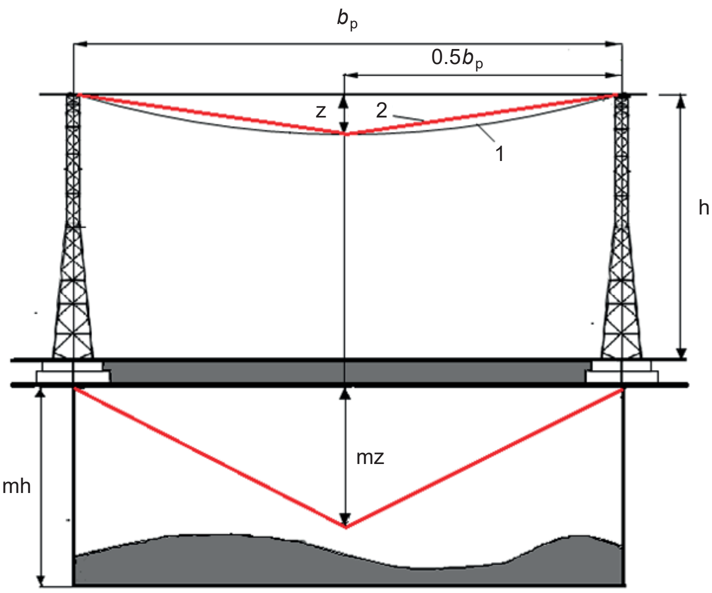

Fig. 7. The span of the line with the hanging conductor (1) and approximation of its shape by line segments (2)

$$k_z = mzb_p/2b_pmh, \tag{3}$$

where: b_p – span length, z – sag dimension. If it is assumed that, for example, "$N_d = 25/\text{year}$; $m = 3.35$; $h = 16$ m; $b_p = 60$ m, $z = 3.5$ m and $b = 5$ km", then the analyzed factor will assume a value of $k_z = 0.11$, which means that in this case the sag will decrease the range of lightning selectivity (which is $N = 0.161/\text{year}$) by line by 11%.

Based on the above assumptions, an analysis of the impact of the proposed kz factor on the lightning risk assessment for several selected overhang values was performed. The obtained results were compared with the values of the operated line with the average conductor sag at the level of 8 m. Therefore, it was assumed that $N_d = 20/\text{year}$; m = 4, 4; h = 15 m. The results of the calculations are shown in Fig. 8.

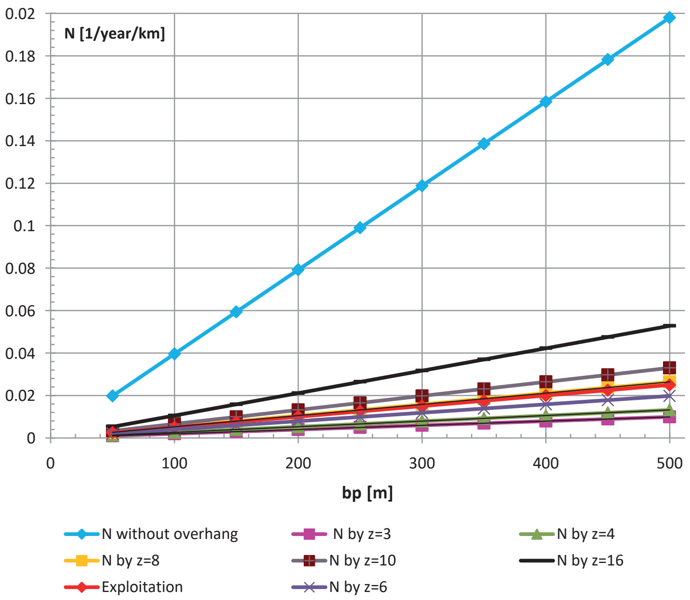

Fig. 8. Dependence of the number of lightning strikes on the length of the overhead line span without sag (theoretical / calculation case) and for different sag values (calculation and operational case)

Based on the relationships shown in Fig. 8, it can be seen that the number of lightning strikes to the line increases linearly as the length of the line increases. However, the case with no sag, which is widely used in calculations for the assessment of lightning risk, significantly differs from the results, where sag was taken into account. Comparing the case without considering the sag with the operational case, it can be seen that a substantial divergence in calculation results appear. Simultaneously, using the coefficient k_z proposed in this article, the analyzed relationships have much lower values without taking the sag into account. That means, in this case, the sag will reduce the range of lightning selectivity across the line by a certain amount. Moreover, the calculation case for 8 m sag is practically equivalent to the operational case, which has a similar average sag value. It confirms that the proposed mathematical model corresponds to the practical layout.

4. Mathematical model considering the object near the line

Refering to second of two aspects selected at the end of Section 3 (influence of near object) the presence of a tree is taken into account in the calculation of the coefficient of the line lightning attraction range reduction, as shown in Figs. 9 and 11.

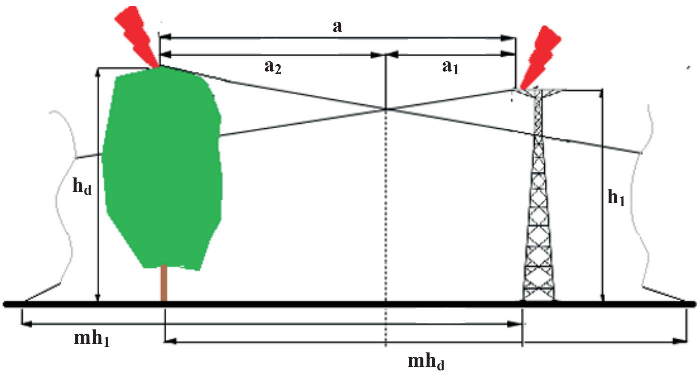

Fig. 9. Representation of the method of reducing the expected number of lightning strikes the line by taking into account the impact of the tree located near the line

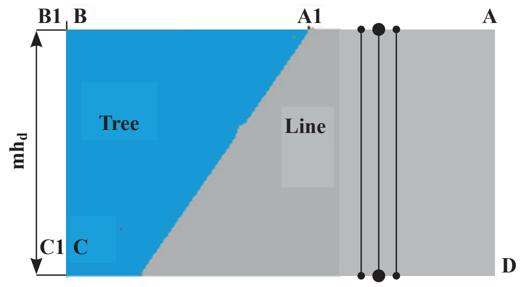

Fig. 10. The zone of lightning selectivity

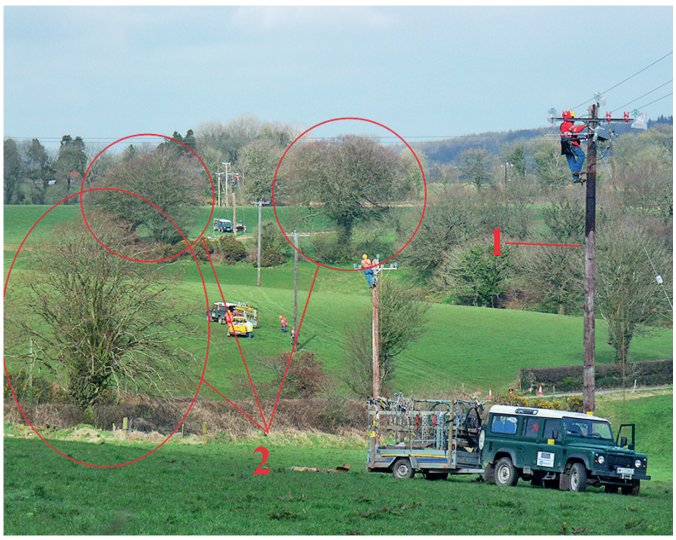

Fig. 11. An example location of objects like tree near the overhead line assuming that $h_d > h_l$ or $h_d = h_l$

Due to the fact that this case is more complicated, calculations can only be made approximately. The distance a between the line and the tree is divided into parts: a_1 and a_2. While moving away from the section a along the power line part a_1 increasing and a_2 decreasing but the relation between their changes remains almost constant.

The zone of lightning selectivity across the line has an area equal to:

$$S_l = 2mh_l 2mh_d = 4m^2 h_d h_l. \tag{4}$$

The ABCD area is the surface of the lightning selectivity area across the line. The surface of the A1B1C1 area is the area of lightning selectivity for the tree we are analyzing. As part of this analysis, it was assumed that the A1B1C1 area is part of the lightning selectivity area of the ABCD line. Area A1B1C1 lightning selectivity for the tree (assuming simplification that the A1C1 segment is straight and not curved) has an equal area (Fig. 10):

$$S_d = 0.5(mh_l - a_1)2mh_d = mh_d(mh_d - a_1). \tag{5}$$

The proportions between the sides of the triangles associated with the line and the tree indicate that:

$$\frac{a_1}{mh_l} = \frac{a_2}{mh_d}, \tag{6}$$

$$\frac{a_1}{h_l} = \frac{(a-a_1)}{h_d}, \tag{7}$$

$$a_1 = \frac{ah_l}{(h_l+h_d)}. \tag{8}$$

The formula for k_d is eventually obtained:

$$k_d = \frac{s_d}{s_l}, \tag{9}$$

$$k_d = \frac{mh_d(mh_1 - a_1)}{4m^2 h_d h_l}, \tag{10}$$

$$k_d = mh_d(mh_1 - ah_l/(h_l+h_d))/4m^2 h_d h_l. \tag{11}$$

This part of the article deals with a lightning strike near a line. This leads to induced overvoltages and to a corresponding non-uniform electric field distribution. Due to the specificity of these processes, the intensity of the electric field depends on current wave parameters such as peak value I [kA], current rise 30 kA$/\mu$s, speed vc [m$/\mu$s] and distance r [m] from the considered line. At the same time, we assume that the electric field strength distribution under the line is averaged. Based on the antenna wave theory [32], we can determine the electric field strength at any point x under the line. The speed c $= 300$ m$/\mu$s is assumed for electromagnetic wave, which is produced by current wave with the speed vc <300 m$/\mu$s and at this assumption the formula (12) has been developed [32].

$$E_h = \frac{30l}{v}\left(-\frac{1}{\sqrt{x^2+r^2}} + \frac{1-v^2}{\sqrt{(vct-x)^2 + r^2(1-v^2)}}\right). \tag{12}$$

The expression given above describes the distribution of the vertical component of the electric field strength along the x axis at a distance r from it. By introducing the quantity by the line height h_l, the coefficient of the impact of the current wave speed reduction k_v into the above formula, we obtain a universal formula for determining the voltage induced [33]:

$$u_i = \frac{30\,lh_l k_v}{r}. \tag{13}$$

Assuming maximum parameters regarding the speed of current wave development and its reduction in the line ($k_v \approx 1.1$) for the value of induced overvoltages that may occur in the line, we obtain a dedicated formula for the value of the voltage induced [33]:

$$u_i = \frac{33\,lh_l}{r}. \tag{14}$$

Taking into account the above formula, Fig. 12 shows the impact of lightning channels in individual cases on the line. In the absence of objects near the line, there is a direct lightning strike (A1-A3). The area that is subject to this influence is within the borders $r_A = mh_l$. In the case of the appearance of individual objects near the line, the area that is subject to the influence of induced surges (B1-B2) in the line increases significantly. The boundary of this area can be described by inequality $mh_l < r_{A/B} < r_{Bmax}$. Therefore, the "safety" limit for the line, i.e. the area where the line is not affected by lightning channels can be described by inequality [33]:

$$r_{Bmax} = \frac{33\,lh_l}{u_w}, \tag{15}$$

in which u_w – withstand voltage of the line insulation.

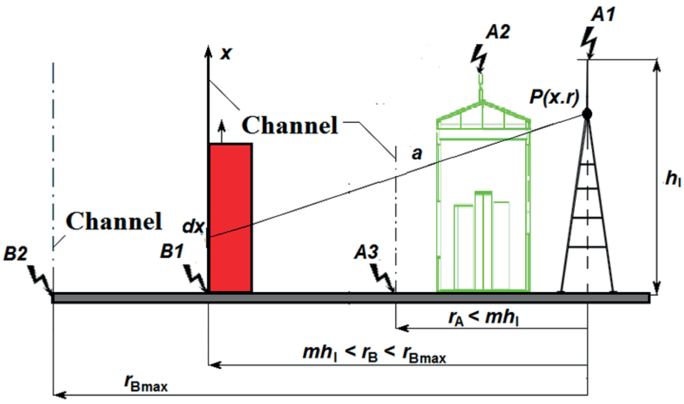

Fig. 12. Demonstration of the division of zones of lightning discharge influence to the line

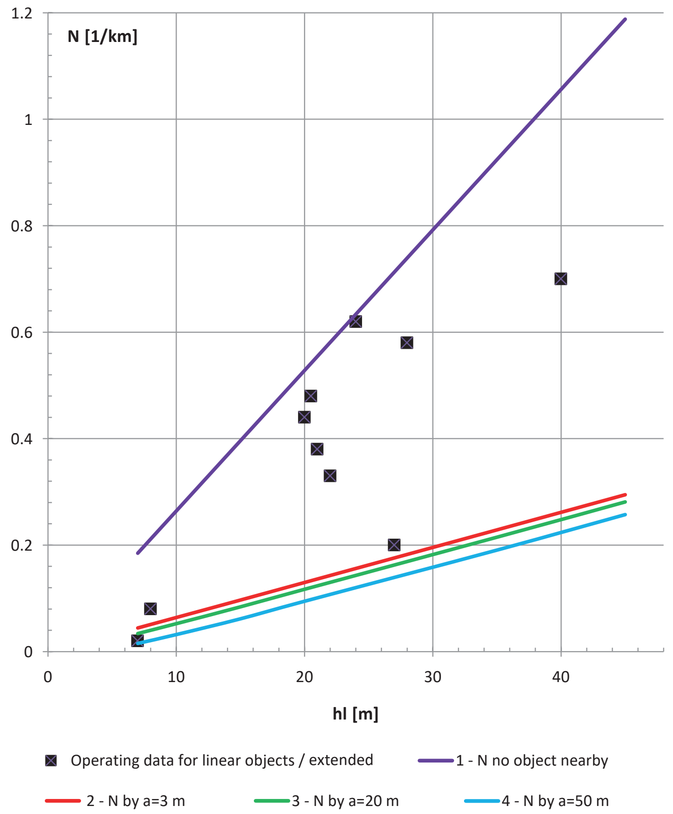

Fig. 13. Relationship between the number of lightning strikes and the height h_l of the long object (overhead line spans) at the value of lightning range a $(a = a_1)$

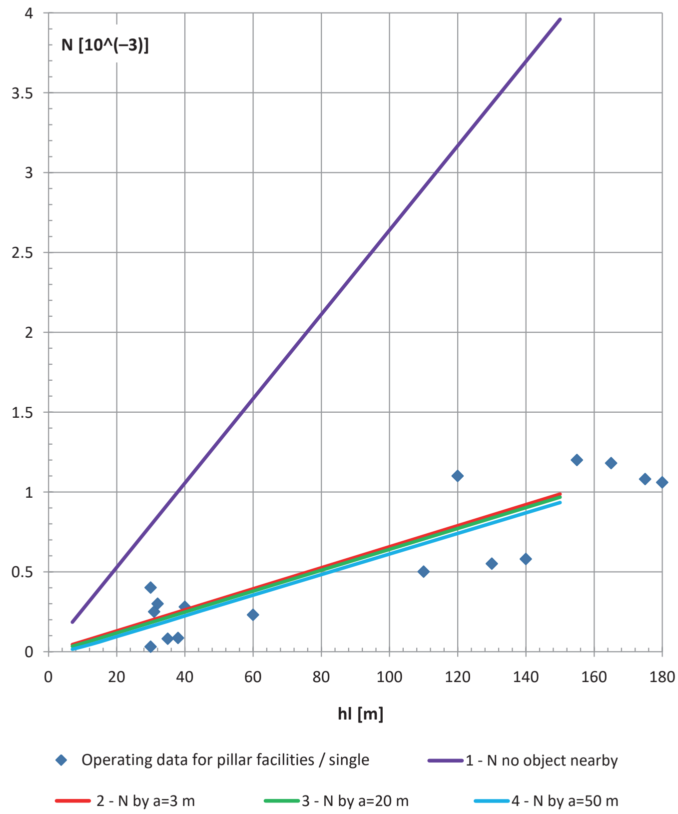

Fig. 14. Dependence of the number of lightning strikes N on the height h_l of a single compact object (overhead line pole/tower) at the value of lightning range a $(a = a_1)$

Based on the above assumptions, calculations were made for selected cases. Due to the fact that energy distributors and power system operators do not have data on lightning strikes on objects close to the line, the following method of analysis of the obtained results is proposed. The results were divided into two groups:

1. Number of lightning strikes a long object, e.g. span (Fig. 13)
2. Number of lightning strikes on an individual object, e.g. tower/pylon (Fig. 14).

For the analysis, several basic cases were adopted with some adaptations:

- Object height near the line smaller than the line height ($h_d = 10$ m, $h_l = 7$ m and $h_d = 12$ m, $h_l = 10$ m).
- The height of the object near the line is equal to the height of the line ($h_d = h_l = 15$ m and $h_d = h_l = 20$ m).
- The height of the object near the line is larger than the height of the line ($h_d = 30$ m, $h_l = 35$ m; $h_d = 40$ m, $h_l = 45$ m and $h_d = 50$ m, $h_l = 70$ m).

As part of the analysis, the first case of lightning striking long spans was first analyzed. The case of lightning striking long spans were analyzed first, with an assumed length of the section of the line is 1 km, and the distance of the object near the line varies between 3 and 50 m. As can be seen in Fig. 13, if the object located near the line is not taken into account, the characteristic of the lightning strike influence on the line which was struck is similar to the case without sag. As mentioned earlier, due to the lack of data regarding lightning strikes to near objects, the obtained results can not be directly compared, however, the relationships in Fig. 12 clearly confirm that objects near the line attract some of the lightnings. This is due to the fact that all curves, including objects near the line, lies below the points that show the number of lightning strikes during operation. Lightning strikes to single compact objects (towers/pylons) are another aspect of this analysis. The insertion of this aspect is aimed at carrying out a various and precise analysis of the obtained results. As part of this analysis, the case $h_d = 50$ m, $h_l = 150$ m was additionally analyzed. Figure 14 shows a slightly different situation when comparing the calculation results and the data from exploitation. At the same time, it can be seen that the dependence curves of the influence of lightning discharge to the line, when taking into account near objects well approximate the set of data from exploitation. This means that the proposed operational model reflects the actual state as averaged data. The proposed mathematical models can be used for the initial estimation of the impact of lightning discharges on the overhead line.

5. Summary

Lightning discharges are the main factor that leads to emergency situations in medium and high voltage power grids.

Lightning strike on the line contributes to power outs and damage to the line's structural elements. The insulator string is one of such structural elements. Reducing the impact of atmospheric overvoltages on the operation of the line is possible by increasing the strength of the overhead line insulation, reducing the grounding resistance of poles and installing lightning conductors or overvoltage protection devices. The possibilities of implementing the above activities are limited:

- Increasing the strength of the overhead line insulation requires modernization of the pole structure.
- It is not possible to provide adequate pole earth resistance for some categories of land.

A maximum of 1 or 2 lightning conductors can be hung on a typical overhead pole. That is why the effectiveness of the above options should be assessed in terms of the costs incurred, taking into account the specificity of individual cases. If it is possible to locate sections of the overhead line with a lower level of protection against atmospheric surges, measures should be taken to eliminate such sections. To such episodes you can refer to:

- Overhead line sections with lower insulation strength (e.g. steel poles in line with wooden poles)
- Sections with high poles (forest poles, crossing poles)
- Sections with high level of earth resistance of the poles
- Sections of overhead lines without lightning conductors and surge protection devices
- Intersections with higher voltage overhead lines.

If it is not possible to isolate sections of the overhead line with a lower level of protection against atmospheric surges and the number Line outages due to these surges are high, it is necessary to lower the surge level simultaneously for the entire line. In this case, we need to choose the appropriate method of surge protection, which forces us to solve tasks such as calculating the protection zone of such devices. Such calculations were made in this article. This article proposes a mathematical model that shows the results with a high level of convergence with the results obtained for the actual state for the number of parameters considered. At the same time, the proposed model ensures efficiency and precision as part of the initial analysis of the impact of lightning discharges on the line in the event of limited data and parameters. The model developed in this article also assumes the possibility of adapting to other power grid facilities, and not only the overhead line.

In the case of the mathematical model of decrease in expected lightning discharges, taking into account the influence of the sag, convergence with exploitation data has been obtained. The presented results show the effectiveness of taking overhangs into account when calculating the impact of lightning discharges on the line. From the obtained results, it can be concluded that the smaller the sag is, the smaller is the coefficient of extension of the range of the lightning selectivity zone by line. At the same time, this ratio increases linearly with increasing sag.

While working on the model preparation, a division of the area adjacent to the line into zones with a specific lightning discharge selectivity and different impact on the line was also developed. Defining the above coefficient makes it possible to precisely determine the level of lightning hazard of the line. If the standard value of overhead line overhang is assumed, we get the following results improvement (Fig. 8):

- For spans up to 100 m (overhead lines up to 110 kV), the number of lightning strikes is four times smaller compared to the results obtained for the current lightning hazard assessment models used on the line.
- For spans from 100 m to 300 m (110 kV overhead lines), the number of lightning strikes is six times smaller compared to the results obtained for the current lightning hazard assessment models used on the line.
- For spans from 300 m to 500 m (220 kV overhead lines and above), the number of lightning strikes is ten times smaller compared to the results obtained for the currently used models of lightning hazard assessment.

In order to execute a multi-criteria analysis of the impact of lightning discharges on overhead lines, the mathematical model considers the influence of near objects. The model takes into account the case of induced overvoltages, which occur due to the fact that part of the strokes to neighboring objects causes an increase in the value of induced voltages in the line and takes into account an increase in the nonuniformity of the electric field distribution under the considered line, based on the wave theory of antennas. For this purpose, the results were analyzed separately for parts that are compact (poles) and long (span of the line).

Additional analysis includes several parameters such as: distance from the line, line height, and object height. It can be explained using results that the range of division of the lightning selectivity zone by the object near the line changes in a narrow range with a change of the object-line distance change. Simultaneously the factor extends linearly with changes of the height of the line and the near object (Fig. 13 and 14).

Considering the above achievement, it will help to increase the precision of the overhead line lightning hazard assessment due to the specificity of the overhead line in the vicinity of objects of different height.

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