ЕНЕРГЕТИЧНІ СИСТЕМИ ТА КОМПЛЕКСИ
ENERGY SYSTEMS AND COMPLEXES

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OVERVIEW OF FACTORS AFFECTING THE ESTIMATION OF LIGHTNING SHIELDING PERFORMANCE OF OVERHEAD TRANSMISSION LINES

This paper examines the risk of lightning stroke to overhead transmission line. The estimation procedure for the lightning performance of overhead power lines is based on the selected lightning attachment model, available lightning parameter statistics, the transmission tower design and voltage levels, type of overvoltage and other characteristics. In this paper the overview of factors affecting the estimation of lightning shielding performance of overhead transmission lines was performed. Among the factors that can affect the estimation accuracy, one can list insufficiently accurate data on the ground flash density in the area of interest and lack of complete data on statistical distribution of lightning current magnitudes. The paper shows that the influence of wind on the increase in the horizontal exposed distance of the phase conductor is not also taken into account. In this research traditional electro-geometric model was used for estimation of lightning performance of 220 kV overhead power line. Results obtained suggest that swing of suspension insulator strings caused by strong winds may lead to increased risk of lightning shielding failure during thunderstorm. Calculation performed for 3 kA lightning current magnitude shows that at swing angle equal to –1 degree, the horizontal unprotected distance of phase conductor increases by 3.1%, that corresponds to 5.240 m uncovered width. When the swing angle is increased to –5 degree, the uncovered width is increased by 15.8% that corresponds to 5.885 m uncovered width. It is proposed that an increase in the risk of lightning shielding failure as a result of wind load can be accounted by applying an appropriate correction factor in expressions for calculation of shielding failure rate, shielding failure flashover rate, etc. Proposed correction factor should account frequency and strength of wind in the area of transmission line route and depend on transmission line voltage level and tower design. Further efforts should be focused on obtaining and justifying the numerical values of this correction factor.

***Keywords**: lightning, shielding failure, overhead ground wire, wind load.*

Introduction.

If for climatologists and meteorologists lightning activity is one of the important indicators of climate change [1], then for power engineers lightning is the cause of overvoltage and transmission line outages. Lightning outages of overhead power lines are most commonly caused by lightning strokes to a tower top, an overhead ground wire (shield wire) or a phase conductor. Transmission line route, tower structure design, impulse insulation strength of insulators used, shielding and grounding may both improve and degrade the lightning performance of overhead transmission lines [2]. Therefore, these appear to be important characteristics for transmission line designers. In lightning protection, lightning performance of transmission line means the annual number of lightning flashes per 100 kilometers (or 100 miles) of line length potentially able to cause insulation flashover [2, 3]. Overhead power lines are usually shielded by one or two overhead ground wires. In lightning protection of overhead power lines, the shielding failure denotes the appearance of a lightning flash that bypasses the shield wires and hit the phase conductor. To estimate lightning shielding failure and possible shielding failure outage, the electro-geometric theory is the most widely used [4, 5]. Various modifications to electro-geometric model such as dynamic electro-geometrical model [6] or elliptic model [7] are also used nowadays. One of a key component in the electro-geometric model concept and rolling sphere method is a striking distance or attractive radius of a lightning flash. Based on this value, the main parameters are calculated, that estimate how effectively the overhead power line is protected from lightning. Here one can list parameters such as shielding failure rate (SFR) or shielding failure flashover rate (SFFOR) for the overhead transmission line. An accurate estimating the lightning shielding performance is important for reduction of lightning outages of overhead power lines. However, by its nature, lightning is an unpredictable phenomenon and has not yet been sufficiently studied. For this reason, all methods of assessing the lightning performance of overhead transmission lines give only an approximate estimation. There are studies [8, 9] showing the measured data may differ from the expected number of lightning strikes to different tall structures calculated based on traditional calculation procedures. This applies to tall structures of various purposes, such as buildings, monuments, bridges, power lines. For example, in [5, 9] observed number of strokes to upper phase of large-sized overhead transmission lines was larger than those derived from calculations according to conventional electro-geometric model. Thus, an analysis of factors that may degrade estimation of lightning shielding performance is important. This study does not deal with the development of a new method for assessing lightning performance of power lines, but about the analysis and refinement of the parameters included in the accepted calculation procedure based on electro-geometric concept.

Purpose of work:

The aim of the work is to continue previous research [10] and make an overview of factors that may affect an accurate estimation of lightning shielding performance of power lines.

Research material.

Traditional electro-geometric model is based on a striking distance aforementioned above. Last step or striking distance of the lightning flash is used to determine the magnitude of prospective stroke current that can bypass the shield wire and hit the phase conductor:

$$r_c = 10 \cdot I^{0.65}, \tag{1}$$

where: r_c is length of last step or striking distance to phase conductor, m; I is the lightning current magnitude, kA. In most cases, striking distances to the overhead ground wire and to the phase conductor are assumed to be equal. Sometimes all striking distances assumed to be equal, including striking distance to the ground [2, 10]. When the lightning current magnitude rises, the striking distances also rise. The cumulative probability of first return stroke current I_f in negative lightning to exceed I is approached by the equation [2]:

$$P(I_f > I) = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.6}} \tag{2}$$

One of most important parameters for lightning performance estimation is the ground flash density (N_g) that denotes the average annual number of lightning strokes to ground per unit area at a given location. Obviously, the higher is the ground flash density value for the specific location, the higher is the expected rate of lightning flashes to the structure in the given area. If the ground flash density data is not available for the specific location, then, depending on the initial data, it can be calculated using one of the following formulas:

$$N_g = 0.04 \cdot T_d^{1.25}, \tag{3}$$

$$N_g = 0.054 \cdot T_h^{1.1}, \tag{4}$$

where: T_d is the keraunic level or number of thunderstorm days in year for the area of interest; T_h is the number of thunderstorm hours in year for given location. The ground flash density in one region of the planet can be very different from the values in another one. The expression (3) is based on the lightning flash data measured with lightning flash counters in South Africa [11] and the range for T_D was varying from 4 to 80. Thus, the data calculated in this way for other regions will be approximate. For example, the annual thunderstorm days count T_d for India is ranging from 1 to 103 [12]. Since N_g is a fundamental parameter that underlies the procedures for calculating the expected number of lightning strikes to any structure, in order to improve the accuracy of the estimate, it is preferable to use not common expression (3), but regional ground flash density values. For example, in [13] it was derived that the ground flash density N_g for conditions of India can be calculated from the formula (5).

$$N_g = 0.026 \cdot T_d^{1.274}. \tag{5}$$

A feature of global lightning activity is that it varies from year to year [14, 15]. That is why more accurate values for ground flash density can be obtained by direct measurements with advanced lightning detection networks built on an evenly distributed network of ground-based sensors [14]. That is more accurate data than obsolete approach using thunderstorm day parameter based upon the audible detection of thunder.

The shielding failure rate (SFR) characterizes an overhead power line with respect to the annual number of shielding failures given per 100 km and defined by the following expression [4].

$$SFR = \frac{2 \cdot N_g \cdot L}{10} \int_{I=I_{\min}}^{I=I_{\max}} D_c(I) \cdot f_1(I) dI, \tag{6}$$

where: N_g is the is the ground flash density, flashes / km^2 / year; L is the transmission line length, km; I_{min} is the minimum lightning current, typically assumed from 0 to 2 kA; I_{max} is the maximum lightning current, kA; $D_c(I)$ is the horizontal exposure width (m) of the phase conductor, as the function of lightning current amplitude; $f_1(I)$ is the density function of the distribution of lightning current amplitude of the first return stroke. The SFR is obtained by integrating the horizontal exposure width D_c, which is varied for different structural design of overhead power transmission towers. Fig. 1 demonstrates lightning shielding failure mechanism for one overhead ground wire and one phase conductor located above a horizontal earth according to classical electro-geometric model. The dotted lines in the illustration show the sagging of the conductors.

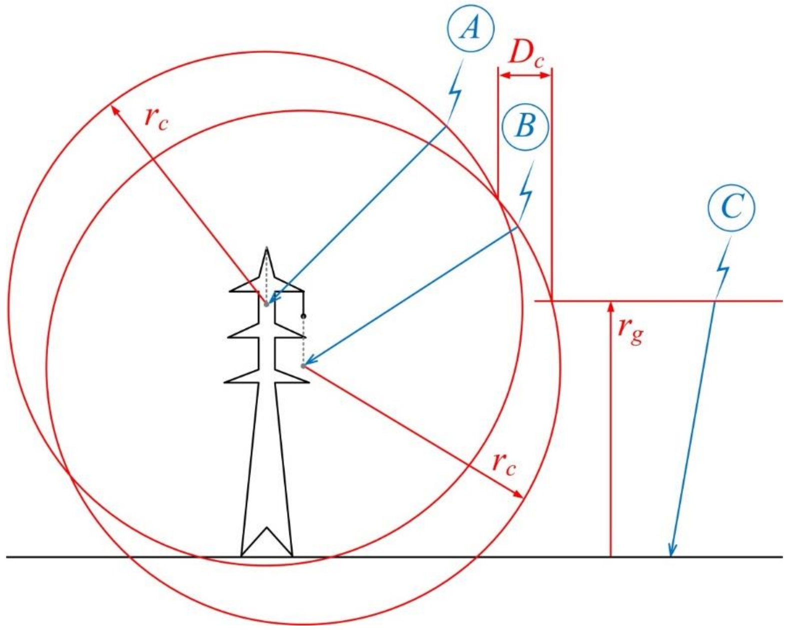

Figure 1 – Initial exposure distance for a shielding failure.

In Fig. 1, as well as below in Fig. 3 and Fig. 4 three downward lightning leaders of the same current magnitude are depicted propagating from thundercloud toward the transmission line. It is assumed that these lightning leaders have sufficient current to create the proper striking distance shown in mentioned illustrations. Downward leader denoted as *A* may strike only the overhead ground wire, because anywhere on the arc it touching, the distance to the phase conductor is too great. Downward leader denoted as *C* may strike only the earth, because anywhere on the straight line it touching, the distance to the phase conductor is also too great. Finally, only one lightning leader denoted as *C* may strike the phase conductor, because anywhere on the arc it touching, the distance to the phase conductor is less than to flat earth or overhead ground wire. For extra and ultra high voltage transmission lines, a lightning shielding failure with low current amplitude may not necessarily lead to an insulation flashover. The minimum or critical current I_c (kA) required for flashover occurrence can be evaluated by equation (7).

$$I_c = \frac{2 \cdot CFO}{Z_{surge}}, \tag{7}$$

where: CFO is the critical impulse flashover voltage meaning the crest value of the impulse wave which causes flashover through the surrounding medium in 50% of the cases this impulse voltage was applied; Z_{surge} is the surge impedance of phase conductor under presence of corona.
The critical current value (7) is required for the calculation of shielding failure flashover rate (SFFOR) characterizing an overhead power line with respect to the annual number of lightning shielding failures which leads to insulation flashover given per 100 km and defined by the following expression [4].

$$SFFOR = \frac{2 \cdot N_g \cdot L}{10} \int_{I=I_C}^{I_{\max}} D_c(I) \cdot f_1(I) dI \,. \tag{8}$$

In case the current of the first stroke is leas than the critical current I_c, subsequent stroke that propagates the same lightning channel may have a current magnitude, sufficient to cause an insulation flashover. The cumulative probability of subsequent stroke current I_s to exceed *I* is approached by the following equation [2]:

$$P(I_s > I) = \frac{1}{1 + \left(\frac{I}{12}\right)^{2.7}} \tag{9}$$

Among the obvious factors that can affect the accuracy of the assessment using formulas (6) and (8), one can single out insufficiently accurate data on the ground flash density N_g in the area of interest and lack of complete data on statistical distribution of lightning current magnitudes. This article advances the hypothesis that another one reason is that the influence of wind on the increase in the horizontal exposed distance D_c of the phase conductor is not taken into account.

The direct influence of wind on the operation of an overhead power line is its load on overhead ground wires, phase conductors and electricity pylons. Due to the lack of knowledge about the wind load, damage and destruction of transmission towers may occur. Besides high intensity winds such as tornadoes and hurricanes, the main causes of tower failures are errors in the value of the calculated wind load, misunderstanding about the nature of the wind load distribution around the structure. The wind gust sets an additional horizontal load on the conductors of the overhead power line, which leads to an increase in the mechanical tension in the conductor material and the deviation of the sagging from the vertical plane. In addition, the deviation of the conductors of adjacent phases under the action of the wind may not occur synchronously. Fig. 2 shows how wind pressure on overhead ground wire may increase the horizontal exposure distance D_c of the phase conductor.

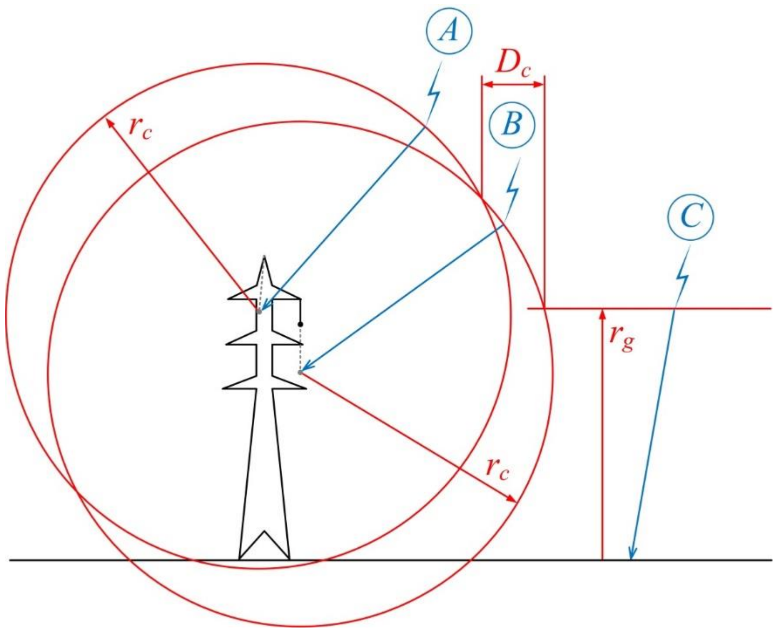

Figure 2 – Increase in exposure distance for a shielding failure due to wind-induced deflections of overhead ground wire.

Another example of horizontal exposure distance rise due to wind pressure on phase conductor is shown in Fig. 3.

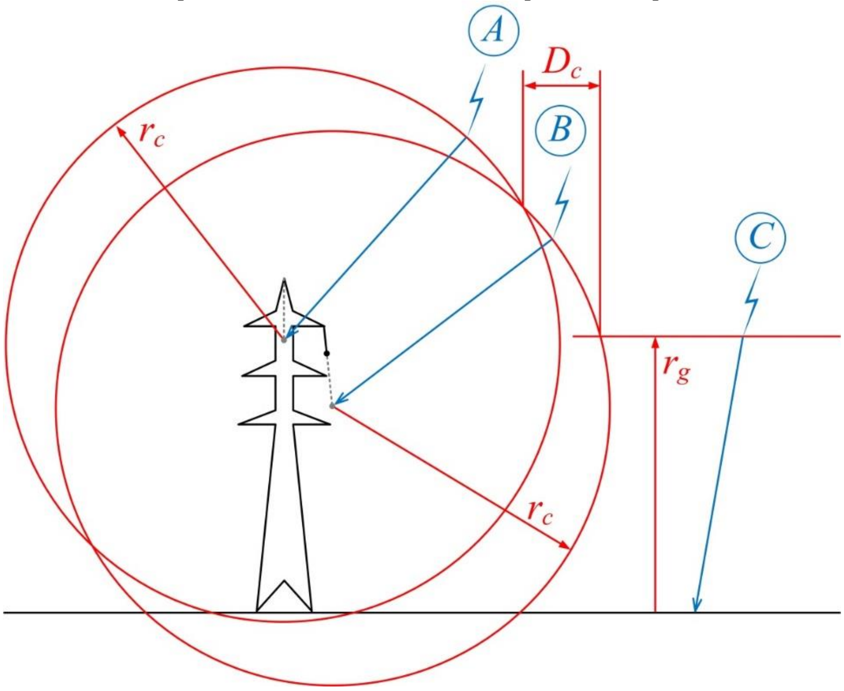

Figure 3 – Increase in exposure distance for a shielding failure due to wind-induced deflections of phase conductor.

Video footage of an overhead power line during wind shows the horizontal deflection of the phase conductors. A couple of video frames are shown in Fig. 4.

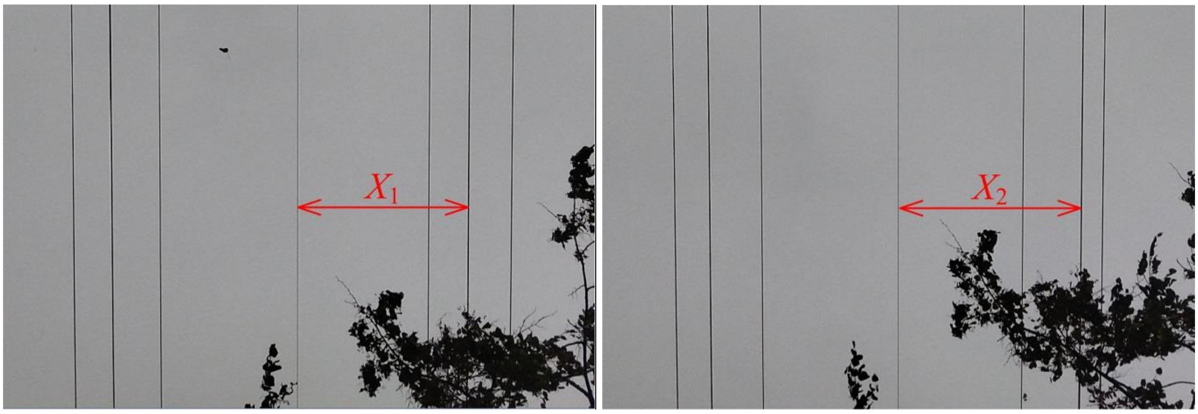

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Figure 4 – Horizontal displacement of phase conductor due to wind gust:
a – starting position (X_1); b – increased horizontal distance (X_2) between the phase conductor and the shield wire under wind gust.

Above photographs show a bottom view of the phase conductors of double circuit transmission line with one overhead ground wire in the middle. Compared to Fig. 4-a, the wind gust causes horizontal distance rise between one of the phase conductors and the overhead ground wire in Fig. 4-a. This theoretically leads to an increase in SFR (6) and SFFOR (8). According to [16], the uncovered width D_c can be calculated through the following steps:

$$\alpha_1 = \arcsin\left(\frac{r_g - y_c}{r_c}\right), \quad (10)$$

$$\alpha_2 = \arctan\left(\frac{x_c - x_g}{y_g - y_c}\right), \quad (11)$$

$$\alpha_3 = \arccos\left(\frac{\sqrt{(x_c - x_g)^2 + (y_g - y_c)^2}}{2 \cdot r_c}\right), \quad (12)$$

$$D_c = r_c \cdot (\cos(\alpha_1) + \sin(\alpha_2 - \alpha_3)), \quad (13)$$

where: r_c is the striking distance to conductors, m; r_g is the striking distance to ground, m; x_c and y_c are the coordinates of a phase conductor, m; x_g and y_g are the coordinates of an overhead ground wire, m.

An example of how the value of the uncovered width D_c may depend on the swing angle of suspension insulator string for a 220 kV line (refer to Fig. 3) in the middle of the span is shown in Table I.

Table I. Effect of swing angle rise on horizontal exposure distance D_c for a shielding failure estimation.

Swing angle suspension insulator string, degree	Uncovered width D_c (refer to Fig. 3), m	Growth, %
0°	5.082 m	–
–1°	5.240 m	3.1 %
–2°	5.400 m	6.3 %
–5°	5.885 m	15.8 %
–10°	6.699 m	31.8 %
–15°	7.494 m	47.5 %

Calculation was performed for 3 kA lightning current magnitude, 3.5 m span value and 2.34 m insulation string length. In Table I negative values of swing angle of suspension insulator strings mean that clearance distance between tower and conductor increases under the influence of wind load (see Fig. 3). Estimation was performed upper phase conductor by expressions (1), (10) – (13) with initial coordinates: x_c = 4.50 m; y_c = 24.73 m; x_g = 0 m; y_g = 32.28 m. Swing of suspension insulator strings in overhead high voltage transmission lines subjected to strong winds may lead to flashovers between the tower heads and phase conductors as the clearance distance between a tower head and a suspended conductor significantly decreases [17]. Results in Table I suggests that swing of suspension insulator strings caused by strong winds may also lead to increased risk of lightning shielding failure during thunderstorm.

It is proposed that an increase in the risk of lightning shielding failure as a result of wind load can be accounted by applying an appropriate correction factor in (6) and (8). For example:

$$SFFOR = \frac{2 \cdot N_g \cdot L}{10} \int_{I=I_c}^{I_{\max}} C_w \cdot D_c(I) \cdot f_1(I) dI \,, \qquad (14)$$

where: C_w is proposed correction factor accounting frequency and strength of wind in the area of transmission line route and depending on transmission line voltage level and tower design.

Conclusions.

The estimation procedure for the lightning performance of overhead power lines is based on the selected lightning attachment model, available lightning parameter statistics, the transmission tower design and voltage levels, type of overvoltage and other characteristics. In this paper the overview of factors affecting the estimation of lightning shielding performance of overhead transmission lines was performed. Among the factors that can affect the estimation accuracy, one can list insufficiently accurate data on the ground flash density in the area of interest and lack of complete data on statistical distribution of lightning current magnitudes. The paper shows that the influence of wind on the increase in the horizontal exposed distance of the phase conductor is not also taken into account. In this research traditional electro-geometric model was used for estimation of lightning performance of 220 kV overhead power line. Results obtained suggest that swing of suspension insulator strings caused by strong winds may lead to increased risk of lightning shielding failure during thunderstorm. Calculation performed for 3 kA lightning current magnitude shows that at swing angle equal to –1 degree, the horizontal unprotected distance of phase conductor increases by 3.1 %. When the swing angle is increased to –5 degree, the uncovered width is increased by 15.8%. It is proposed that an increase in the risk of lightning shielding failure as a result of wind load can be accounted by applying an appropriate correction factor in expressions for calculation of shielding failure rate, shielding failure flashover rate, etc. Proposed correction factor should account frequency and strength of wind in the area of transmission line route and depend on transmission line voltage level and tower design. Further efforts should be focused on obtaining and justifying the numerical values of this correction factor.

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ОГЛЯД ФАКТОРІВ, ЩО ВПЛИВАЮТЬ НА ОЦІНКУ ЕФЕКТИВНОСТІ БЛИСКАВКОЗАХИСТУ ПОВІТРЯНИХ ЛІНІЙ ЕЛЕКТРОПЕРЕДАЧІ

У цій статті розглядається ризик удару блискавки в повітряну лінію електропередачі. Процедура оцінки ефективності блискавкозахисту повітряних ліній електропередачі базується на обраній моделі приєднання блискавки, наявній статистиці параметрів блискавки, конструкції опори лінії електропередачі та рівнях напруги, типі перенапруг та інших характеристиках. У цій статті було проведено огляд факторів, що впливають на оцінку ефективності блискавкозахисту повітряних ліній електропередачі. Серед факторів, які можуть вплинути на точність оцінки, можна назвати недостатньо точні дані щодо густини спалахів блискавки до землі в досліджуваній області та відсутність повних даних щодо статистичного розподілу величин струму блискавки. У статті показано, що вплив вітру на збільшення горизонтальної незахищеної відстані до фазного провідника також не прийнято до уваги. У цьому дослідженні традиційна електрогеометрична модель була використана для оцінки грозозахисту повітряної лінії електропередачі класу 220 кВ. Отримані результати свідчать про те, що хитання підвісної гірлянди ізоляторів, викликане сильним вітром, може призвести до підвищеного ризику відмови блискавкозахисту під час грози. Розрахунок, проведений для амплітуди струму блискавки 3 кА, показує, що при куті повороту, що дорівнює –1 градусу, ширина горизонтальної незахищеної ділянки до фазного провідника зростає на 3,1%, що становить 5,240 м. При збільшенні кута розгойдування до –5 градусів ширина незахищеної ділянки збільшується на 15,8%, що становить 5,885 м. Запропоновано, що зростання ризику відмови блискавкозахисту в результаті вітрового навантаження можна врахувати шляхом внесення відповідного коригувального коефіцієнта до виразів для розрахунку частоти відмов блискавкозахисту, частоти перекриттів ізоляції через відмову блискавкозахисту тощо. Запропонований коригувальний коефіцієнт має враховувати частоту та силу вітру в районі траси лінії електропередачі і залежати від класу напруги лінії електропередачі та конструкції опори. Подальші зусилля мають бути спрямовані на отримання та обґрунтування числових значень даного коригувального коефіцієнта.

Ключові слова: *блискавка, відмова грозозахисту, грозозахисний трос, вітрове навантаження.*

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