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ASSESSMENT OF WIND-INDUCED EFFECTS ON LIGHTNING SHIELDING PERFORMANCE OF OVERHEAD POWER TRANSMISSION LINES

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Purpose. This article aims to provide an overview of research concerning the influence of wind-induced effects on the lightning shielding performance of overhead power transmission lines. **Methodology.** The study utilizes the Electrogeometric Model (EGM) as a foundation and examines how wind-induced conductor movement affects lightning attachment points. The EGM, a widely recognized mathematical model, offers insights into the lightning shielding performance of transmission lines. The analysis considers wind pressure, lightning current magnitude, and conductor sway. **Results.** Observations reveal that while the EGM provides estimations of lightning attachment points, it does not account for dynamic conductor effects. Wind-induced conductor movement can alter the lightning shielding failure zone, potentially exposing phase conductors to direct lightning strikes. Calculations using the EGM confirm the impact of wind-induced movement on shielding failure width. Even at relatively low wind pressure of 100 Pa (12.78 m/s), the width of the unprotected zone increases to 150.28% at a lightning current of 3 kA and to 191.12% at a current of 5 kA. **Originality.** This work expands on existing lightning protection assessments by incorporating wind-induced effects and conductor dynamics. The study highlights discrepancies between EGM-calculated and observed lightning strikes and explains the role of conductor deflection in these variations. **Practical Value.** The findings emphasize the importance of considering wind-induced conductor movement in lightning protection strategies for overhead transmission lines. The study underscores the need for more comprehensive models that account for conductor dynamics and environmental conditions. **Conclusions.** Wind-induced movement of shield wires and phase conductors can significantly influence lightning shielding performance. The study calls for advanced modeling techniques that incorporate conductor dynamics, meteorological data, and specific line characteristics to provide more accurate and reliable assessments of lightning protection. References 15, figures 4.

Key words: lightning stroke, overhead power transmission line, wind pressure, electro-geometric model.

Problem statement. Lightning strikes pose significant risks to overhead power transmission lines, potentially leading to costly downtime, equipment damage, and safety hazards. The Electro-Geometric Model (EGM) is a widely recognized and essential tool for evaluating the lightning shielding performance of overhead power transmission lines [1, 2]. Developed as a simplified mathematical model, the EGM serves as an initial estimation approach, offering valuable insights into lightning attachment points on transmission lines without the need for comparatively extensive computational resources or intricate site-specific data [3, 4]. New simulation methodologies and advanced lightning protection analyses typically build upon the core concepts of the EGM while incorporating additional complexities and more accurate representations of real-world scenarios [5, 6]. Such methodologies strive to overcome some of the limitations of the EGM and provide more comprehensive and precise lightning protection assessments.

The EGM is primarily focused on predicting the termination points of lightning strikes on the power line. It does not explicitly model the full lightning strike process or the complex behavior of lightning discharges. In the EGM, the shield wires and phase conductors are treated as static conductors, and it does not account for dynamic effects such as conductor movement due to wind or thermal expansion.

While the EGM provides a useful and straightforward approach for estimating the lightning attachment points, it does have limitations due to its simplified assumptions. In real-world situations, wind-induced conductor movement and other dynamic effects can influence the actual lightning attachment points on the transmission line.

For more accurate lightning performance assessments, advanced modeling techniques that consider conductor dynamics, meteorological data, and the specific characteristics of the transmission line should use. These models should account the effects of conductor motion and provide a more comprehensive evaluation of the lightning shielding performance of overhead power lines. However, they also tend to be more complex and require additional data and computational resources.

In view of the foregoing, the aim of this article is an overview of current state of research on wind-induced effects on lightning shielding performance of overhead power lines.

Material and results. While overhead transmission lines can have environmental impacts, the environment can also affect the performance and integrity of transmission lines [7, 8]. Several environmental factors can influence transmission lines, potentially leading to operational challenges and structural issues.

In cold climates, ice and snow can accumulate on the conductors and the transmission line structures. The added weight of ice can increase the mechanical loading on the towers and conductors, leading to sagging and potential damage [9]. Ice accretion on the conductors can also alter the aerodynamic behavior, affecting the line's dynamic stability and causing increased conductor movement under wind forces.

Lightning strikes pose a significant threat to overhead transmission lines. When lightning strikes the power line, it can cause flashovers, arcing, and transient overvoltages, which may damage the line's insulation and connected equipment. Lightning can also lead to power outages and affect the reliability of the electrical grid.

Temperature fluctuations can cause thermal expansion and contraction of the conductors and the power line structures. Significant temperature variations can lead to changes in line sag, affecting the clearance between the conductors and the ground or other objects. Additionally, thermal cycling can accelerate the aging of materials and contribute to long-term degradation of the transmission line components.

In coastal regions or areas with high humidity, corrosion can be a concern for transmission line structures. Salt-laden air and other pollutants can lead to accelerated corrosion of the metal components, potentially compromising the structural integrity of the power line.

Overgrown vegetation, especially trees and branches in close proximity to transmission lines, can pose a risk of conductor contact during windy conditions. This can result in flashovers and power interruptions [10].

Wind is one of the most significant environmental factors affecting overhead transmission lines. Strong winds can exert mechanical forces on the power line structures, causing them to vibrate and sway [11, 12]. Wind-induced movement can lead to conductor galloping, conductor slap, and increased tension on the wires, potentially leading to fatigue and wear over time. Extreme wind events like hurricanes or typhoons can result in severe damage to the transmission lines, including broken conductors or collapsed towers.

Recent studies show that wind can affect the lightning shielding performance of overhead power transmission lines [7, 13]. Lightning protection for power lines is primarily achieved through the use of shielding wires or cables, also known as ground wires or static wires, which are installed above the conductors. These shielding wires help to intercept lightning strikes and provide a path for the lightning current to safely flow into the ground.

Strong winds can cause the shielding wires to sway or move, potentially altering their position relative to the power conductors. If the shielding wires are displaced too far from the conductors, their ability to intercept lightning strikes may be reduced, increasing the risk of lightning-induced damage to the power line.

The wind-induced movement of the phase conductors in overhead power lines can also affect the lightning shielding performance. When wind causes the phase conductors to sway or move, their position relative to the shielding wires may change. These irregularities can enhance the likelihood of lightning strikes directly to the phase conductors, increasing the chances of damage to the power line.

Calculations performed using the EGM confirm above assumptions [7]. The Fig. 1 demonstrates lightning shielding failure mechanism according to EGM concept, when the shielding wire is swaying or moving under the action of a wind load.

In the same way, the Fig. 2 shows lightning shielding failure mechanism, when the phase conductor is swaying or moving under the influence of a wind load.

In the EGM for lightning shielding analysis in overhead power transmission lines, the lightning shielding failure zone refers to the area around the transmission lines where the lightning protection system may not effectively prevent lightning strikes from hitting the phase conductors [3, 4].

In the EGM, the lightning shielding failure zone is determined based on the calculation of shielding failure arcs. These arcs represent the regions around the transmission lines where the electric field strength exceeds a critical threshold, making it possible for lightning to strike the phase conductors rather than being intercepted and conducted safely to the ground through the shielding system.

The lightning shielding failure zone arises due to various factors, including the geometry and height of the transmission line conductors, the presence of shield wires or overhead ground wires, and the

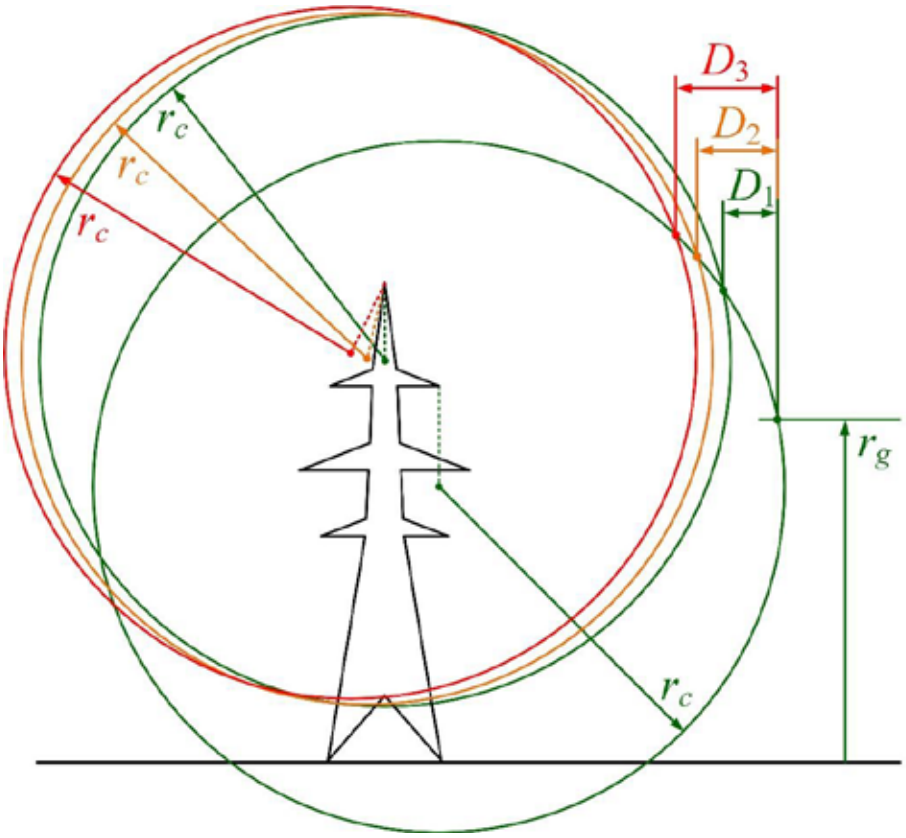

Fig. 1. Computation representation of lightning shielding failure arcs due to wind-induced movement of shield wire in EGM

characteristics of the surrounding environment. The EGM aims to estimate the most probable locations where lightning could bypass the protective shielding and directly strike the phase conductors, leading to potential damage and operational interruptions.

To calculate all the striking distances of the lightning flash in Fig. 1 and Fig. 2 the following expression was used:

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

where: r_c is the striking distance of the lightning flash in metres; I is the lightning current magnitude in kiloamperes.

In the EGM, the exposure distance for a shielding failure or the shielding failure width denotes that, when downward lightning leader occurs within the shielding failure width (D_1, D_2 and D_3 in Fig. 1 and Fig. 2), there is a higher likelihood of lightning striking the phase conductors directly, bypassing the shielding wires. It's important to note that the EGM provides a probabilistic estimation of the striking distance. Lightning is a stochastic and unpredictable phenomenon, and the actual lightning attachment points can vary. Therefore, the striking distance calculated using the EGM represents the most probable location for lightning attachment, but lightning strikes can occur at other locations as well.

The shielding failure width is calculated through the following steps [3, 4]:

$$\alpha_1 = \arcsin\left(\frac{r_g - y_c}{r_c}\right), \tag{2}$$

$$\alpha_2 = \arctan\left(\frac{x_c - x_{sw}}{y_{sw} - y_c}\right), \tag{3}$$

$$\alpha_3 = \arccos\left(\frac{1}{2} \cdot \frac{\sqrt{\left(x_c - x_{sw}\right)^2 + \left(y_{sw} - y_c\right)^2}}{r_c}\right), \tag{4}$$

$$D = r_c \cdot \left(\cos\left(\alpha_1\right) + \sin\left(\alpha_2 - \alpha_3\right)\right), \tag{5}$$

where: D is the shielding failure width; r_c is the striking distance to the phase conductor; r_g is the striking distance to the earth; x_c and y_c are the coordinates of the phase conductor; x_{sw} and y_{sw} are the coordinates of the shielding wire. All values are in metres.

The EGM was used for the middle of the span in Fig. 1 and Fig. 2. Observations show [14], that light-

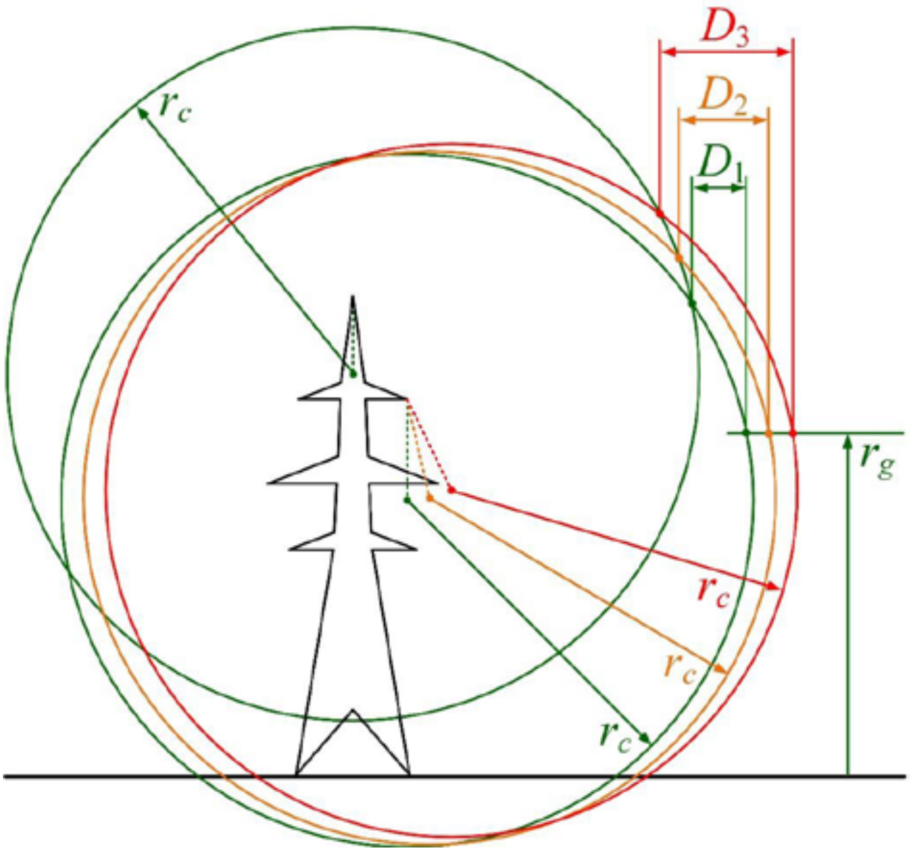

Fig. 2. Computation representation of lightning shielding failure arcs due to wind-induced movement of phase conductor in EGM

ning strikes can hit overhead power transmission lines directly, including the phase conductors, at any point along the span between transmission line support structures (towers or poles). Lightning does not always strike only at the endpoints or towers; it can also strike the transmission line in the middle of the span. Observations also show [14], that in large-scale overhead power transmission lines, lightning is more likely to directly strike the upper phase conductor compared to the middle or lower ones. For this reason, this article focuses on the upper phase sway. It's important to note that while the upper phase conductor is more likely to be directly struck by lightning, all phase conductors in the vicinity can still be at risk during a lightning event (Fig. 3). Lightning strikes can have complex paths and may involve multiple strokes, leading to transient overvoltages and other effects on the entire transmission line.

Fig. 3. Statistics about direct lightning strokes to phase conductors of ultra-high voltage transmission lines based on [14]

The Fig. 4 shows how the phase conductor sway during thunderstorm may affect the lightning shielding failure width on the example on the 220 kV overhead transmission line [13].

Wind pressure on the phase conductor is defined by the equation:

$$P = 0.61 \cdot V^2 , \qquad (6)$$

where: P is the wind pressure in Pascals; V is the air velocity in metres per second.

Even at relatively low wind pressure of 100 Pa (12.78 m/s), the width of the unprotected zone increases to 150.28% at a current of 3 kA and to 191.12% at a current of 5 kA. The initial value is the width of the lightning shielding failure zone in the absence of wind load, when the wires are static (4.167 m at 3 kA lightning current and 2.825 m at a 5 kA lightning current).

Theoretically, at maximum design wind pressure of 800 Pa in the middle of the span, the width of the lightning shielding failure zone can increase to 432.28% at a current of 3 kA and to 773.49% at a current of 5 kA.

With a further increase in the rated lightning current, where is a minimum lightning current magnitude at which the complete lightning shielding can be achieved. According to the EGM, this means that the width of the lightning shielding failure is equal to zero. At higher current values, the phase conductors, being completely protected in the absence of wind or a small wind, become unprotected when the wind load increases.

Overall, deflections of the shield wire or phase conductor can indeed affect the lightning shielding performance of an overhead transmission line, especially when there is a thundercloud above the transmission line at that moment. These deflections can impact the overall effectiveness of the lightning protection system and may increase the risk of direct lightning strikes to the phase conductors (refer to Fig. 1 and Fig. 2).

There are studies, showing there are discrepancies between the calculated values from the EGM and the measured numbers of direct lightning strokes to overhead transmission lines [15]. Lightning strikes are inherently stochastic events, meaning they are random and influenced by various unpredictable factors such as the specific atmospheric conditions, local topography, and charge distribution within thunderstorms. The EGM provides estimates based on simplified assumptions and deterministic calculations, which may not capture the full randomness of lightning strikes.

This work shows that such discrepancies can be partly explained by the fact that the existing models do not take into account the deflection of conductors under the influence of wind.

Conclusions. This article examines a critical aspect of lightning protection in overhead power transmission lines: the influence of wind-induced conductor movement on lightning shielding performance. The study underscores that while the Electro-Geometric Model (EGM) provides a valuable initial estimation approach, its limitations in capturing dynamic conductor behavior and wind effects necessitate further investigation. The analysis reveals that wind-induced movement of shield wires and phase conductors can lead to significant alterations in the

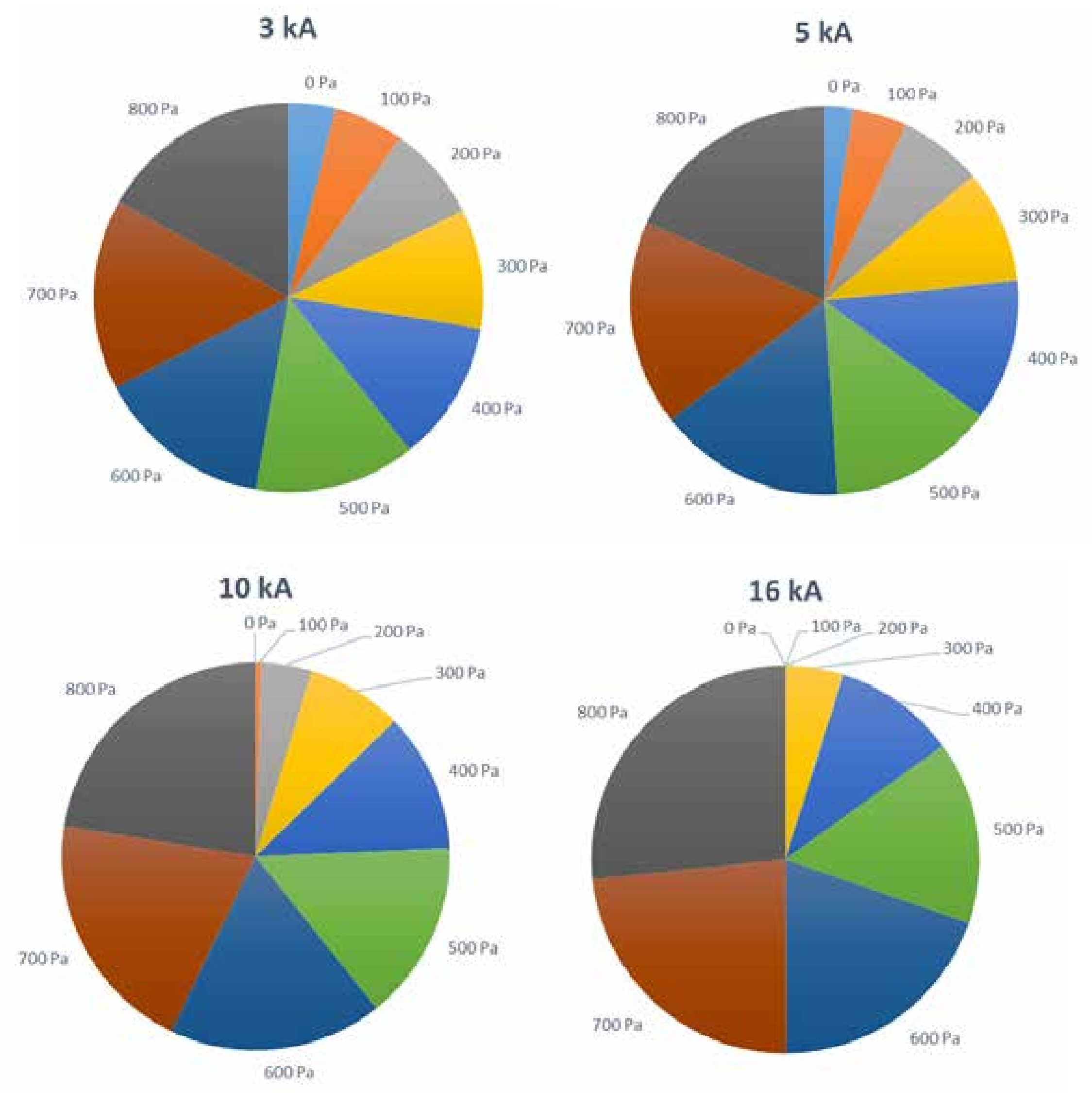

Fig. 4. Comparative increase in the shielding failure width depending on the wind pressure on the phase conductor for various lightning current magnitudes based on [13]

lightning shielding failure zone. This dynamic phenomenon can expose phase conductors to a higher risk of direct lightning strikes, potentially compromising the insulation of the entire transmission line and its associated infrastructure. As highlighted, advancements in lightning protection analysis require models that go beyond the EGM's simplifications. Incorporating conductor dynamics, meteorological data, and site-specific characteristics will provide a more accurate representation of lightning shielding performance. While these advanced models may demand additional computational resources and data inputs, their enhanced accuracy and reliability justify their implementation.

In the broader context, this study highlights the intricate interplay between environmental factors, complex electrical phenomena, and engineering considerations. In summary, the research presented here provides a stepping stone toward more comprehensive lightning protection strategies that effectively address the challenges posed by wind-induced conductor movement. It serves as a call to action for ongoing research, collaboration, and innovation in the field of lightning protection.

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ОЦІНКА ВПЛИВУ ВІТРУ НА ЗАХИСТ ВІД БЛИСКАВКИ ПОВІТРЯНИХ ЛІНІЙ ЕЛЕКТРОПЕРЕДАЧІ

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Дана стаття має на меті надати огляд досліджень, що стосуються впливу вітру на захист від блискавки повітряних ліній електропередачі. У роботі використано електрогеометричну модель (ЕГМ) для вивчення того, як рух провідника, спричинений вітром, впливає на точки приєднання блискавки. ЕГМ є широко визнаною математичною моделлю, що дає змогу оцінити ефективність блискавкозахисту ліній електропередачі. Аналіз ураховує тиск вітру, величину струму блискавки та коливання провідника. Спостереження показують, що хоча ЕГМ дає змогу оцінити точки приєднання блискавки, вона не враховує динамічні ефекти провідників. Рух провідника, спричинений вітром, може змінити зону відмови блискавкозахисту, потенційно піддаючи фазні провідники прямим ударам блискавки. Розрахунки з використанням ЕГМ підтверджують вплив руху, спричиненого вітром, на ширину зони відмови блискавкозахисту. Навіть за відносно невеликого тиску вітру 100 Па (12,78 м/с) ширина незахищеної зони збільшується до 150,28% за струму блискавки 3 кА і до 191,12% – за струму 5 кА. Дана робота розширює існуючі методи оцінки блискавкозахисту шляхом урахування ефектів вітру та динаміки провідників. Дослідження підкреслює розбіжності між розрахованими за ЕГМ і спостережуваними ударами блискавки та пояснює роль відхилення провідника у цих відмінностях. Отримані дані підкреслюють важливість урахування руху провідника, спричиненого вітром, у стратегіях блискавкозахисту для повітряних ліній електропередачі. Дослідження підкреслює потребу в більш комплексних моделях, які враховують динаміку провідника та умови навколишнього середовища. Переміщення грозозахисних тросів і фазних провідників, спричинене вітром, може значно вплинути на ефективність захисту від блискавки. Дослідження підкреслює потребу в удосконалених методах моделювання, які враховують динаміку провідників, метеорологічні дані та конкретні характеристики лінії, щоб забезпечити більш точну та надійну оцінку блискавкозахисту.

Ключові слова: удар блискавки, повітряна лінія електропередачі, тиск вітру, електро-геометрична модель.

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