UDC 621.316.9
DOI https://doi.org/10.32782/1995-0519.2023.5.12

ASSESSMENT OF CONDUCTOR SAGGING EFFECTS ON LIGHTNING SHIELDING PERFORMANCE OF OVERHEAD POWER TRANSMISSION LINES

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Purpose. This article aims to conduct a detailed analysis of the lightning shielding failure width in overhead power transmission lines, with a specific focus on considering sagging effects at crucial points along the transmission line. **Methodology.** The electro-geometric model was employed for the analysis, accounting for factors such as transmission line tower height, conductor spacing, and shielding wire geometry. Sagging effects were incorporated into the model to provide a more realistic representation of the transmission line's geometry. **Results.** Modeling results revealed that the shielding failure width varies along the transmission line, with smaller values observed at the middle of the span compared to the transmission line tower, differing more than 1.5 times for the studied line. It was found that for the same current value of 7.596 kA, a lightning flash can strike a specific phase conductor near the transmission line tower, but be intercepted by the lightning shield wire at the midspan. **Originality.** This research contributes comprehensive insights into the dynamics of lightning shielding failure, emphasizing the importance of considering sag effects in the design of overhead power transmission lines. **Practical value.** Understanding and optimizing the shielding failure width is crucial for engineers designing lightning protection systems. The findings offer practical implications for reducing the risk of outages and ensuring the reliability of power transmission systems. **Conclusions.** The study demonstrates that sag effects significantly influence the shielding failure width along overhead transmission lines. By considering sag dynamics in the design process, engineers can optimize lightning protection measures, ultimately enhancing the resilience of power transmission infrastructure.

Key words: lightning strike, overhead transmission line, conductor sagging, electro-geometric model.

Problem statement. Shielding failure due to direct lightning strokes is a significant concern in the context of overhead transmission lines. Direct lightning strikes on phase conductors can pose a threat to the reliability and functionality of power transmission systems. Shielding failure occurs when the shielding system, typically composed of shield wires, fails to adequately intercept the lightning flash and conduct the lightning current to the ground. This failure can result in a flashover, where the electrical discharge travels along the surface of the insulators and other components of the transmission line, potentially causing damage and disruption.

The electro-geometric model (EGM) is often employed to analyze and design the geometry of overhead transmission lines to reduce the risk of shielding failure [1; 2]. This model considers factors such as the height and configuration of the transmission towers, and the spacing between conductors. By optimizing these parameters, engineers aim to enhance the ability of the transmission line shield wires to intercept lightning strikes and safely conduct the resulting currents to the ground [3; 4].

The shielding failure width, also referred to as the exposure width [5; 6], is a crucial parameter in the context of lightning protection for overhead power transmission lines. This width represents the lateral distance along the transmission line within which a descending lightning leader might strike the phase conductors, potentially leading to shielding failure.

The specific formula for calculating the shielding failure width may vary based on the exact methodology and assumptions used in a particular implementation of the electro-geometric model [7]. Often the general concept involves considering the average heights of the shield wire and phase conductor along the transmission line to determine the lateral extent within which shielding must be effective [5].

However, including sagging in the analysis provides a more realistic representation of the transmission line's geometry and can improve the accuracy of predictions related to shielding effectiveness and the potential for shielding failure.

In view of the foregoing, the aim of this article is more detailed analysis of the lightning shielding failure width, that involve considering the sagging effects at various points along the transmission line.

Material and results. The shielding failure rate (SFR) is a measure used in the context of lightning protection for overhead power transmission lines [5]. It represents the rate at which shielding failures occur on the transmission line due to direct lightning strokes. The shielding failure rate is usually expressed in terms of the number of shielding failures per unit length (e.g., per kilometer or per 100 kilometers) of the transmission line per unit of time (e.g., per year):

$$SFR = 2 \cdot N_g \cdot L \cdot \int_{I=0}^{I=I_{\max}} W(I) \cdot f_1(I) \cdot dI, \qquad (1)$$

where: N_g is the ground flash density (average number of lightning strokes to the ground per unit area per unit time at a specific location); L is the transmission line length in kilometers; W is the shielding failure width in meters, I is the crest value of the prospective lightning current in kiloamperes; $f_1(I)$ is the probability density of the first return stroke current; I_{max} is that value of lightning current, when the effective shielding is achieved, and the shielding failure width is equal to zero. In the literature, this maximum current is often referred to as the maximum shielding failure current [7; 8].

In the electro-geometric model used for analyzing lightning protection, the shielding failure width is a measure of the area around the transmission line where the shield wires need to effectively intercept the descending lightning leader. The goal is to ensure that the shield wires are positioned optimally to capture the lightning strike and conduct the associated current safely to the ground. This lateral distance or exposure width is influenced by various factors, including the height and configuration of the transmission towers, the spacing between the phase conductors and the shield wires, and the characteristics of the surrounding environment. Engineers use this information to design transmission lines that can minimize the risk of shielding failure and enhance the overall lightning protection performance. Modeling shows that smaller values of the shielding failure width take place at middle of the span than at the transmission tower as a result of reduced height and shielding angle (Fig. 1).

In Fig. 1 a typical double circuit 220 kV lattice power transmission line tower was considered [9]. Here and below, the dotted line indicates the maximum sag of the lightning shield wire and phase conductor in the middle of the span. Due to the lower height of conductors above the ground, the shielding failure width in the middle of the span (horizontal width of arc *CD*) is smaller than at the transmission tower (horizontal width of arc *AB*), reaching 1.254 m and 3.407 m, correspondingly. Likewise, the current value at which full shielding is achieved will be less in the middle of the span than directly at the support.

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

$$r = A \cdot I^B, \qquad (2)$$

where: r is the striking distance of the lightning flash in meters; I is the crest value of the prospective lightning current in kiloamperes; $A = 10$ and $B = 0.65$.

The shielding failure width was calculated through the following procedure:

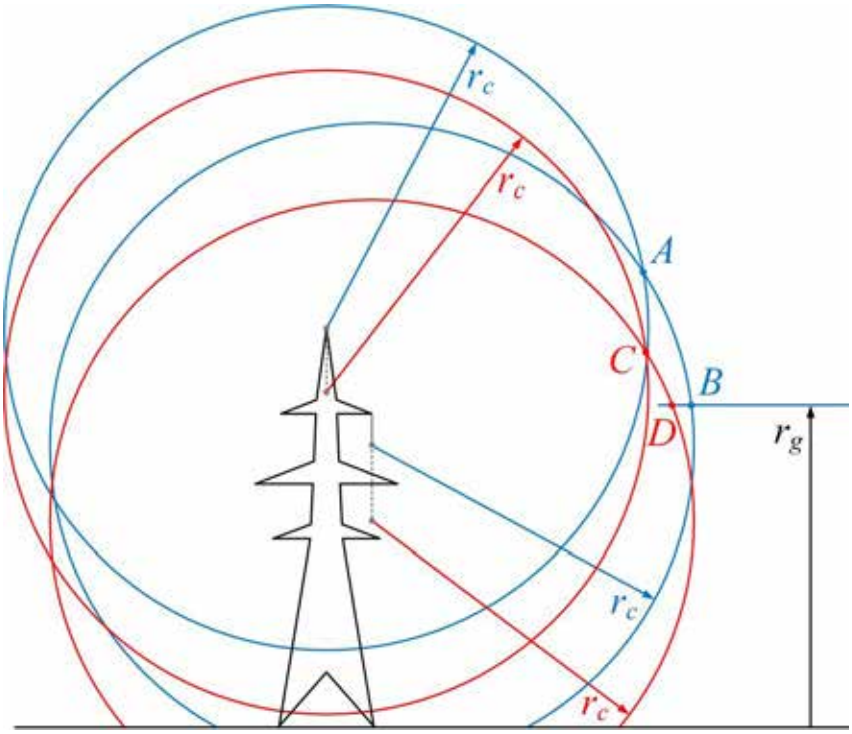

Fig. 1. Comparison between the shielding failure width at the tower (shown in blue color) and at the middle of the span (shown in red) in EGM

$$\alpha_1 = \arcsin\left(\frac{r_g - y_c}{r_c}\right), \quad (3)$$

$$\alpha_2 = \arctan\left(\frac{x_c - x_{sw}}{y_{sw} - y_c}\right), \quad (4)$$

$$\alpha_3 = \arccos\left(\frac{1}{2}\cdot\frac{\sqrt{(x_c - x_{sw})^2 + (y_{sw} - y_c)^2}}{r_c}\right), \quad (5)$$

$$W = r_c \cdot \left(\cos(\alpha_1) + \sin(\alpha_2 - \alpha_3)\right), \quad (6)$$

where: W is the lightning shielding failure width; r_c is the striking distance of the lightning flash to the phase conductor and shield wire; r_g is the striking distance of the lightning flash to the ground; x_c and y_c are the coordinates of the phase conductor; x_{sw} and y_{sw} are the coordinates of the shielding wire. For the considered transmission line, it is assumed, that: $x_c = 4.2$ m; $y_c = 19.2$ m; $x_{sw} = 0$; $y_{sw} = 31.208$ m in the middle of the span, and $x_c = 4.2$ m; $y_c = 26.291$ m; $x_{sw} = 0$; $y_{sw} = 37.115$ m at the transmission tower.

Likewise, the prospective lightning current value at which complete shielding is achieved will be less in the middle of the span than directly at the transmission line pylon (Fig. 2).

Fig. 2 displays the case when, with the same value of the expected lightning current, the complete shielding is achieved at the middle of the span, but still not at the transmission line tower. By setting the some initial current value and giving it small increment, through the iterative calculation procedure using formulas (2)–(6), it was established that this current value is 7.596 kA. However, at the transmission line tower the vertical lightning flash of the same current magnitude, having reached the arc *AB*, bypasses the shield wire and hits the phase conductor.

The value of lightning current, at which the effective shielding is achieved, can also be approximately calculated using the formula (based on [7]):

$$I_{\max} \approx \left(\frac{\gamma\cdot(y_{sw} + y_c)\cdot 0.5}{A\cdot\left(1 - \gamma\cdot\frac{x_c}{\sqrt{x_c^2 + (y_{sw} - y_c)^2}}\right)}\right)^{\frac{1}{B}}, \quad (7)$$

where: $\gamma = 1$ for the approach adopted in this article to determine the values of striking distance of the lightning flash to the phase conductor, shield wire and ground.

According to (7), the approximate value of maximum shielding failure current at the middle of the span is 7.680 kA, which is very close to the value

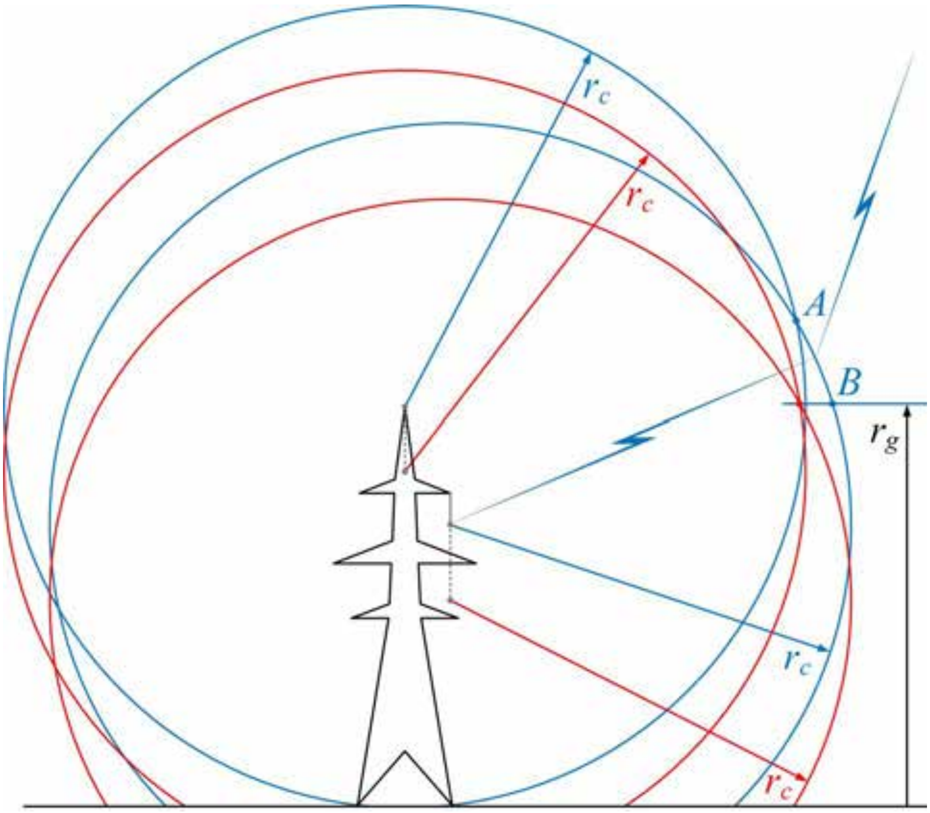

Fig. 2. Reaching the complete shielding at the middle of the span (while still having incomplete shielding at the transmission line pylon) in EGM

obtained above. At the transmission line tower, the complete lightning shielding is achieved at a higher lightning current value of 11.703 kA (Fig. 3).

According to (7), the approximate value of maximum shielding failure current at the transmission line tower is 11.774 kA, which is also very close to the value calculated previously.

The average conductor height, given by the height at the transmission line tower minus two-thirds of the middle span sag. The use of average conductor height in calculations gives smaller value of 8.844 kA, at which the effective shielding is achieved, and zero shielding failure width is reached. According to (7), the approximate value of this lightning current is 8.922 kA.

This work shows that by understanding and optimizing the shielding failure width, engineers can enhance the lightning protection measures on overhead transmission lines, reducing the risk of outages and ensuring the reliability of the power supply infrastructure. It is essential to consider factors such as the height and configuration of the transmission line towers [7], the geometry of the conductors, the conductivity of the ground [10], and the effect of a terrain topography [11]. Recent studies show that wind-induced conductor movements affect the lightning attachment points, and therefore can affect the lightning shielding performance of overhead power lines [12]. The goal is to optimize the design to minimize the risk of lightning-related damage to the power transmission system.

Conclusions. In this study, a detailed analysis of the lightning shielding failure width for overhead power transmission lines was conducted, with a specific focus on considering sagging effects at various points along the transmission line. The electro-geometric model was employed for this analysis, taking into account factors such as the height and configuration of transmission line towers, spacing between conductors, and shielding wire geometry. The modeling results revealed that the shielding failure width varies along the transmission line, with smaller values observed at the middle of the span compared to the transmission tower. This variation is attributed to the reduced height and shielding angle at midspan. The inclusion of sagging effects in the analysis provided a more realistic representation of the transmission line's geometry. Accounting for conductor sag improved the accuracy of predictions related to shielding effectiveness, demonstrating the importance of considering dynamic factors in lightning protection studies. The calculation of striking

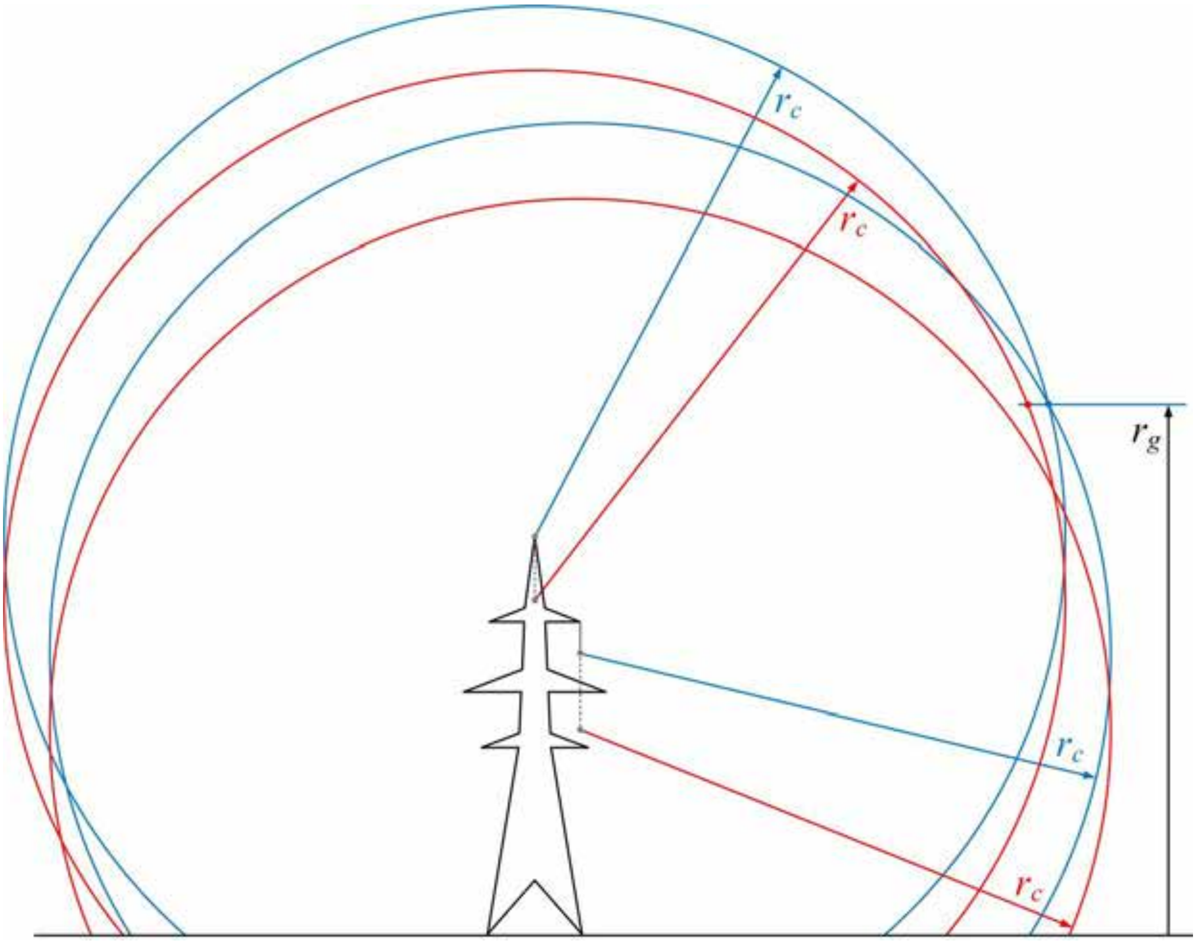

Fig. 3. Reaching the complete shielding at the transmission line pylon and, accordingly, along the entire line in EGM

distances of lightning flashes involved an iterative procedure using specific formulas. The results indicated that, with the same expected lightning current value, complete shielding was achieved at the middle of the span while still incomplete at the transmission tower. The approximate values of the maximum shielding failure current were determined using a formula based on the electro-geometric model. The results showed that the current value at which effective shielding is achieved is lower at the middle of the span compared to the transmission tower. The findings underscore the importance of understanding and optimizing the shielding failure width in engineering design. Engineers can use this knowledge to enhance lightning protection measures, reduce the risk of outages, and ensure the reliability of power transmission systems.

In summary, this work contributes valuable insights into the factors influencing lightning shielding failure along overhead power transmission lines. By refining the understanding of the shielding failure width and considering sagging effects, engineers can make informed decisions in designing effective lightning protection systems for power transmission infrastructure.

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ОЦІНЮВАННЯ ВПЛИВУ ПРОВИСАННЯ ПРОВІДНИКІВ НА ЗАХИСТ ВІД БЛИСКАВКИ ПОВІТРЯНИХ ЛІНІЙ ЕЛЕКТРОПЕРЕДАЧІ

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Метою статті є детальний аналіз ширини зони відмови блискавкозахисту на повітряних лініях електропередачі з особливим акцентом на розгляді ефектів провисання в основних точках уздовж лінії електропередачі. Для аналізу використано електрогеометричну модель, яка враховувала такі фактори, як висота опори лінії електропередачі, відстань між провідниками та геометрія грозозахисного тросу. У моделі враховано ефекти провисання, щоб забезпечити більш реалістичне подання геометрії лінії електропередачі. Результати моделювання показали, що ширина зони відмови блискавкозахисту змінюється вздовж лінії електропередачі, при цьому менші значення спостерігаються в середині прольоту порівняно з ділянкою біля опори лінії електропередачі, відрізняючись більше ніж у 1,5 раза для досліджуваної лінії. Установлено, що за однакового значення струму 7,596 кА спалах блискавки може влучити в окремий однофазний провідник поблизу опори лінії електропередачі, але бути перехопленим грозозахисним тросом усередині прольоту. Дослідження сприяє всебічному уявленню про динамічні властивості зони відмови блискавкозахисту, підкреслюючи важливість урахування ефектів провисання під час проєктування повітряних ліній електропередачі. Розуміння й оптимізація зони відмови блискавкозахисту має вирішальне значення для інженерів, які проєктують системи блискавкозахисту. Отримані результати надають практичні висновки для зниження ризику відключень і забезпечення надійності систем передачі електроенергії. Дослідження демонструє, що провисання провідників значно впливає на ширину зони відмови блискавкозахисту вздовж трас повітряних ліній електропередачі. Ураховуючи динаміку провисання провідників у процесі проєктування, інженери можуть оптимізувати заходи захисту від блискавки, зрештою підвищуючи стійкість систем передачі електроенергії.

Ключові слова: удар блискавки, повітряна лінія електропередачі, провисання провідників, електрогеометрична модель.

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Стаття надійшла 13.09.2023