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Research Article

Investigation of the Parameters of Non-Cylindrical Ice Load on Power Transmission Lines

Ali AJDER*

Yildiz Technical University, Faculty of Electrical and Electronics, Department of Electrical Engineering, 34220, Istanbul-Turkey
* **Corresponding Author**: **Email:** aliajder@yildiz.edu.tr - **ORCID:** 0000-0001-9411-4452

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Abstract:

Ice load on transmission lines is a critical factor that affects their cost and operation. National standards specify how ice load is considered in the design of power lines and poles. These standards generally use empirical relations that assume that the ice load on each phase accumulates uniformly and cylindrically. However, field tests and fault records show that the actual ice load on conductors is often not cylindrical due to altitude, wind strength and direction, and terrain topography. This study firstly defines several parameters to describe asymmetrical ice load. This load can cause additional vertical force on the line, conductor swing angle deviation, and sag changes. Since empirical equations are only valid for cylindrical ice load, the cross-sectional shape of the conductor must be transferred to millimeter paper, and calculations performed using one of several numerical integral methods. The coefficients for asymmetric ice are calculated in kg/m (N/m) using an AutoCAD model in the numerical study.

1. Introduction

National standards and regulations define the design principles of power transmission lines. For example, DIN VDE 0210 (Germany), ÖVE-L11 (Austria), LeV (Switzerland), NBR 5422 (Brazil), GB50545 (China), NESC (USA), KTP 18 (Albania) and Electricity Network Regulation, Electricity High Current Facilities Regulation (Turkey) are some of these national standards/regulations. For each country, different criteria are determined according to transmission line designs, considering the existing conditions [1]. The IEC 80626 is the international standard for the design of transmission lines [2]. Ice load is one of the most important parameters considered in mechanical calculations of power transmission lines [3]. The ice load accreted on the phase conductors and the protection wire causes forces in the vertical direction, leading to the selection of large-scale cross members, diagonals, and vertical brackets and increasing the cost of poles. Even if the transmission line design is well designed, the extra ice loads over time can cause conductors to break and cause energy loss [4]. Even if the line does not rupture, when the wind force acts on the conductor while it is ice-loaded, the conductor's oscillation angle changes, resulting in unexpected problems [5,6].

Ice load (ice cover) accreted on conductors can be formed in different structures such as hoarfrost, crystalline hoarfrost, frost, crystalline ice, and snow load formed as a result of the adhesion of wet snow on the conductor during the sudden change of weather. Another critical parameter for ice load on transmission lines is the icing speed. According to TS IEC 60826 Standard, the water content in the air, wind speed, the average volume of ice particles, ambient temperature, and dimensions of the icy object are defined as factors affecting the icing speed.

Below -10 °C, the water composition in the air decreases, so icing of overhead lines is generally not observed. However, an ice load of 8 kg/m has been recorded in Switzerland even at air temperatures below -20 °C (with strong winds). TS IEC 60826 Standard recommends that the ice load be reflected in the design of the lines with the help of measurements, statistical data on wind and air temperature, and mathematical models.

The ice load should be obtained from measurements taken from conductors representing the line [7]. These measurement methods are defined in IEC

61774 [8]. Ice accretion models from different studies can help with ice data measurement, but verification with actual results is required [9]. The terrain effect is critical for ice accumulation calculations [10]. Since the terrain structure dramatically affects the icing mechanism, transferring data from one area to another causes inaccurate measurements. As a result, icing data obtained from metering stations like or near the line route are required for transmission line designs [2].

TS IEC/TR2 61774 describes icing models in the literature. These models represent model characteristics such as the type of climatic data required and the form of predicted accreted ice.

Accordingly, in the transparent ice model, the thickness of ice accumulation on power transmission lines is estimated using a correction factor based on the diameter of the icy conductor updated at regular intervals of 1 hour. This correction factor is inspired by another study on wind tunnels [11].

In the hoarfrost model, the icing intensity on an object is estimated based on factors such as wind speed, precipitation rate, and temperature. The ice load is calculated by considering the effects of changing the diameter of ice accumulation [12].

In the sleet model, only sleet accumulation is predicted based on factors such as precipitation, snowfall, wind speed, and air temperature. The model uses observed data to determine the average amount of snow thickness and density. Snowmelt is also considered due to factors such as dispersion and reflection.

In the clear ice, hoarfrost, and sleet model, all three types of icing are predicted based on climatic data and the surface characteristics on which the ice is accreted. Ice accretion rate, accretion efficiency, and other factors are calculated to determine the mass and thickness of ice on the conductors. The model updates the conductor diameter and surface properties at each time step to simulate ice formation on transmission lines [13].

The ice and sleet model was developed for simulation studies on power transmission lines. Three-dimensional, time-dependent mathematical models for predicting cylindrical elongation and axial expansion consider the effect of ice/snow load and aerodynamic moment on the rotation and torsion of the conductor, as well as the position of the accretion area along the wind direction [14].

The geometry of ice loads, which are highly effective at high altitudes above sea level with extreme icing and simultaneous storms, can deviate from the cylindrical shape of the field. This study summarizes the calculation of cylindrical ice loads and provides practical definitions and mathematical relations for non-cylindrical ice loads.

2. Material and Methods

2.1 Calculation of Ice Load on Power Transmission Lines

There is no analytical relation for calculating ice load on transmission lines; generally, empirical relations have been developed as a function of conductor diameter $d\,(mm)$ using historical operating information and meteorological and topographical data in countries.

According to EN 50341-3 Standard in European countries, ice load $g_i\,(N/m)$ is formulated as a function of conductor diameter $d\,(mm)$ under some conditions as in other countries. In some cases, it is defined directly. In all these relations, ice is assumed to be cylindrical, symmetrical, and uniformly collected in phase conductors. According to this assumption, the weight of the ice load in the conductor $g_i\,(kg/m)$, the ice diameter $d_i\,(mm)$, and the ice density $\rho_i\,(kg/dm^3)$ are related in Equation 1:

$$d_i = \sqrt{[d^2 + 1274 \times g_i \times \rho_i^{-1}]} \tag{1}$$

The $icing\ rate\,(kg/m/h)$ is the rate at which ice (kg/m) accretes on the conductor for 1 hour. There are empirical relations between $icing\,rate$ and amount of precipitation $y\,(mm/h)$, air temperature t (°C), and wind speed $v\,(km/h)$ given in Equation 2-5 [15].

$$icing\ rate = 0.00061 + 0.00245y \tag{2}$$

$$icing\ rate = e^{at} - e^{[b(t+c)]} + d \quad \{a, b, c, d\text{: } empirical\ coefficients\} \tag{3}$$

$$icing\ rate = 0.01 - 0.00208v \quad \{parallel\ wind\} \tag{4}$$

$$icing\ rate = -0.005 + 0.00095v \quad \{steep\ wind\} \tag{5}$$

If the ice loads $g_{i_1}\,(kg/m)$ and $g_{i_2}\,(kg/m)$ of a conductor at T_1 and T_2 are known, the icing rate at time $T = T_1 - T_2\,(h)$ is calculated by Equation 6.

$$icing\ rate = \frac{g_{i_2} - g_{i_1}}{T_2 - T_1} \quad (kg/m/h) \tag{6}$$

In Equation 6, minus sign (-) for the icing rate at period T indicates that the ice is in the process of melting. Figure 1 shows a perspective view of the ice load accumulated on the phase conductor. In addition to the accumulation of ice load on the phase conductors, it can also accumulate on the protection wires. These different scenarios should be considered separately in ice load analysis.

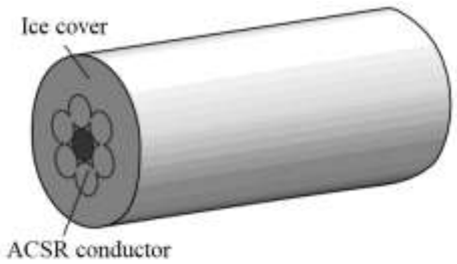


Figure 1. *3D model of cylindrical ice cover in a phase conductor*

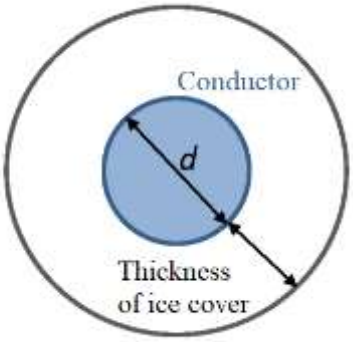


Figure 2. *Thickness of cylindrical icing*

According to TEIAS Project Technical Specifications, the thickness of ice on a conductor δ_b is accepted as 0 for Zone I, 15 (mm) for Zone II, 20 (mm) for Zone III, and 30 (mm) for Zone IV. Figure 2 shows the case where cylindrical icing occurs. Equation 7 is used to calculate the ice thickness.

$$d_i = d + 2 \times ice\ thickness \qquad (7)$$

2.2 Definition of Non-Cylindrical (Asymmetric) Ice Load in Power Transmission Lines

2.2.1 Partial Ice Load

While the accumulation of ice is generally considered uniform for the whole conductor, due to the nature of the terrain, the sun's rays incident on the icy conductor may be partially blocked by a mountain, trees, or any other obstacle. As a result, part of the ice cover may melt and fall off, called the 'partial ice load' problem in the literature on power transmission lines.

Assuming uniform icing, the conductor only move in the vertical direction, whereas under partial ice load, there may be slippage in both vertical and horizontal directions. The possibility of partial ice loading needs to be examined in the design of relatively more critical transmission lines passing through areas with a high density of natural obstacles. With symmetrical pole span and uniform ice loading, the 'horizontal tangent point' occurs at the center of the pole span $(a/2)$, whereas with partial ice loading, the horizontal tangent point will shift towards the suspension point according to the moment effect [16].

2.2.2 Non-Cylindrical Ice Load

During the design of transmission lines, ice accretion is assumed to be 'cylindrical'; however, for unforeseen reasons, the ice cover on conductors or protection wires may only sometimes be cylindrical. In such cases, the sample of non-cylindrical ice cover is examined at ice load monitoring stations for analysis. The ice cover sample taken from the conductor is sliced, and cross-sectional photographs are taken for each slice. Perspectives of the conductor and ice cover are obtained according to the averages of the measurement values taken from different points of the x and y axes in the photographs taken. This information is used during the design of the ice cover.

The relation $g_i = k\sqrt{d}\ (kg/m)$ applies to cylindrical icing. Therefore, for asymmetric icing, the cross-sectional photograph of the ice is imported to millimeter paper, and the area of the ice cover is calculated using one of the numerical integration methods (Trapezoidal, Simpson, Durand, et al.) or AutoCAD modelling. The approximate weight (kg/m) is obtained from the sample's length and the density of ice.

Skewness

The skewness in terms of icing because of ice cover forming on a particular surface of the conductor while the other section of the same contour remains bare is defined as in Equation 9.

$$Skewness\ (\varepsilon) = \frac{arc\ length\ of\ bare\ conductor}{perimeter\ of\ conductor} \qquad (9)$$

Degree of Deviation from Cylindrical Shape

The degree of deviation $(\boldsymbol{v})$ from the cylindrical shape can be approximated by Equation 10.

$$v \approx \left(\frac{d_{i_{avg}}}{d'_{i_{avg}}} - 1\right) \times 100 \quad (\%) \qquad (10)$$

If the ice cover is cylindrical $\boldsymbol{v = 0}$ since the numerator and denominator will be equal in Equation 10.

Shape Coefficient

The average ice thickness $(\overline{\boldsymbol{\delta}_i})$, depending on the short and long diameters of the ice cover, can be obtained by Equation 11:

$$\overline{\delta_i} = \frac{1}{2}\sqrt{d_{i1}d_{i2}} - \frac{d}{2} \quad (mm) \qquad (11)$$

In Equation 11, $\boldsymbol{d}\ (\boldsymbol{mm})$ is the diameter of the conductor. Equivalent cylindrical ice thickness can be calculated from Equation 12, where $\{area = area\ of\ ice + area\ of\ conductor\}$

$$\delta_i = \sqrt{\frac{area}{\pi}} - \frac{d}{2} \quad (12)$$

The shape coefficient ($\boldsymbol{\sigma}$), which indicates the amount by which the ice cover deviates from the cylindrical shape, is calculated by dividing Equation 12 by Equation 11.

Degree of Flatness

If there is an elliptical ice cover surrounding the conductor with $\boldsymbol{d_{b_X}} > \boldsymbol{d_{b_Y}}$, the degree of flatness ($\boldsymbol{\alpha}$) can be approximated using Equation 13:

$$\alpha \approx \left(\frac{d_{i_X}}{d_{i_Y}} - 1\right) \times 100 \quad (\%) \quad (13)$$

Degree of Sharpness

If $\boldsymbol{d_{i_Y}} > \boldsymbol{d_{i_X}}$ in the ice cover surrounding the conductor for the shape of an ellipse, then the degree of sharpness ($\boldsymbol{\beta}$) is defined, which is approximated in Equation 14.

$$\beta \approx \left(\frac{d_{b_Y}}{d_{b_X}} - 1\right) \times 100 \quad (\%) \quad (14)$$

Ovality of the Ice Cover

The ovality ($\boldsymbol{\gamma}$) can be calculated from the $\boldsymbol{d_{max}}$ and $\boldsymbol{d_{min}}$ measurements taken from the cross-section of the ice cover as in Equation 15:

$$\gamma = \left|\frac{d_{max} - d_{min}}{(d_{max} + d_{min})/2}\right| \times 100 \quad (\%) \quad (15)$$

If more precise calculations for $v, \sigma, \alpha, \beta, \gamma$ are desired, arithmetic averages can be used by taking different slices from the icy conductor sample.
Numerical integration methods can be used to calculate the average ice load, average wind-exposed lateral area, average degree of deviation of the ice cover from the cylindrical shape, average degree of flatness, and average ice flatness using a scaled image of the non-cylindrical ice cover along the span.

Unbalanced Icing

An unbalanced ice load can be defined as the exposure of phase or bundle conductors forming phases to different ice covers. The degree of unbalanced icing $\boldsymbol{\lambda_a}$ can be calculated for $phase\ a$ using Equation 16.

$$\lambda_a = \left|1 - \frac{g_{i_a}}{\overline{g_\iota}}\right| \times 100 \quad (\%) \quad (16)$$

In Equation 16, $\overline{\boldsymbol{g_b}}$ is the arithmetic average of the $phases\ a, b, c$ ($phases\ a, b, c \quad a', b', c'$ if the pole is a double circuit). Calculating $\overline{\boldsymbol{g_i}}$ with camera recordings taken from different locations on the relevant transmission line is possible.

For single circuit lines

$$\overline{g_\iota} = \frac{g_{i_a} + g_{i_b} + g_{i_c}}{3} \quad (kg/m) \quad (17)$$

For double circuit lines

$$\overline{g_\iota} = \frac{g_{i_a} + g_{i_b} + g_{i_c} + g_{i_{a'}} + g_{i_{b'}} + g_{i_{c'}}}{6} \quad (kg/m) \quad (18)$$

3. Results and Discussions

A single-circuit power transmission line with double protection wires is handled for the numerical study. The protection wires are galvanized steel conductors with a cross-section of 95 mm2. The phase conductors are steel-cored aluminum (ACSR) conductors with an outer diameter of 30 mm. Cardinal conductor with 954 MCM cross-section 54 aluminum 7 steel cores has a diameter of 30.42 mm, and Rail conductor with 954 MCM cross-section 45 aluminum 7 steel cores has a diameter of 29.61 mm; therefore, the conductor diameter is approximately 30 mm.
The area of the transmission line is in zone III of the Ice Load Map of Turkey (ice load coefficient, k = 0.3). The density of ice (ρb) is accepted as 0.6 kg/dm3 in the Regulation on Electrical Power Plants; however, ρb = 0.70 kg/dm3 is taken here by the ‘Technical Specification for Pole Design for High Voltage Power Transmission Lines of TEIAS’ [17]. Figure 3 shows an example of non-cylindrical icing on the phase conductor, and Figure 4 shows an example of non-cylindrical icing on the double protection wires. In Figure 3 (d), the horizontal scale is 1:2000, and the vertical scale is 1:1. Non-cylindrical icing examples in the phase conductor in Figure 3 (a), (b), (c), (d), and non-cylindrical icing examples in the protection wires in Figure 4 (a) and (b) are modelled in AutoCAD with all details. The results of the calculations using the definitions of non-cylindrical ice loads are given in Table 1 for each sample separately.

4. Conclusions

Among other extra loads on power transmission lines, the formation of non-cylindrical / asymmetric ice loads accelerates the aging of phase conductors and protection wires. Moreover, under the ice load, the angle of oscillation of single and bundle conductors changes with the effect of wind The conductor or protection wire exhibits an aerodynamically unstable movement in the span.

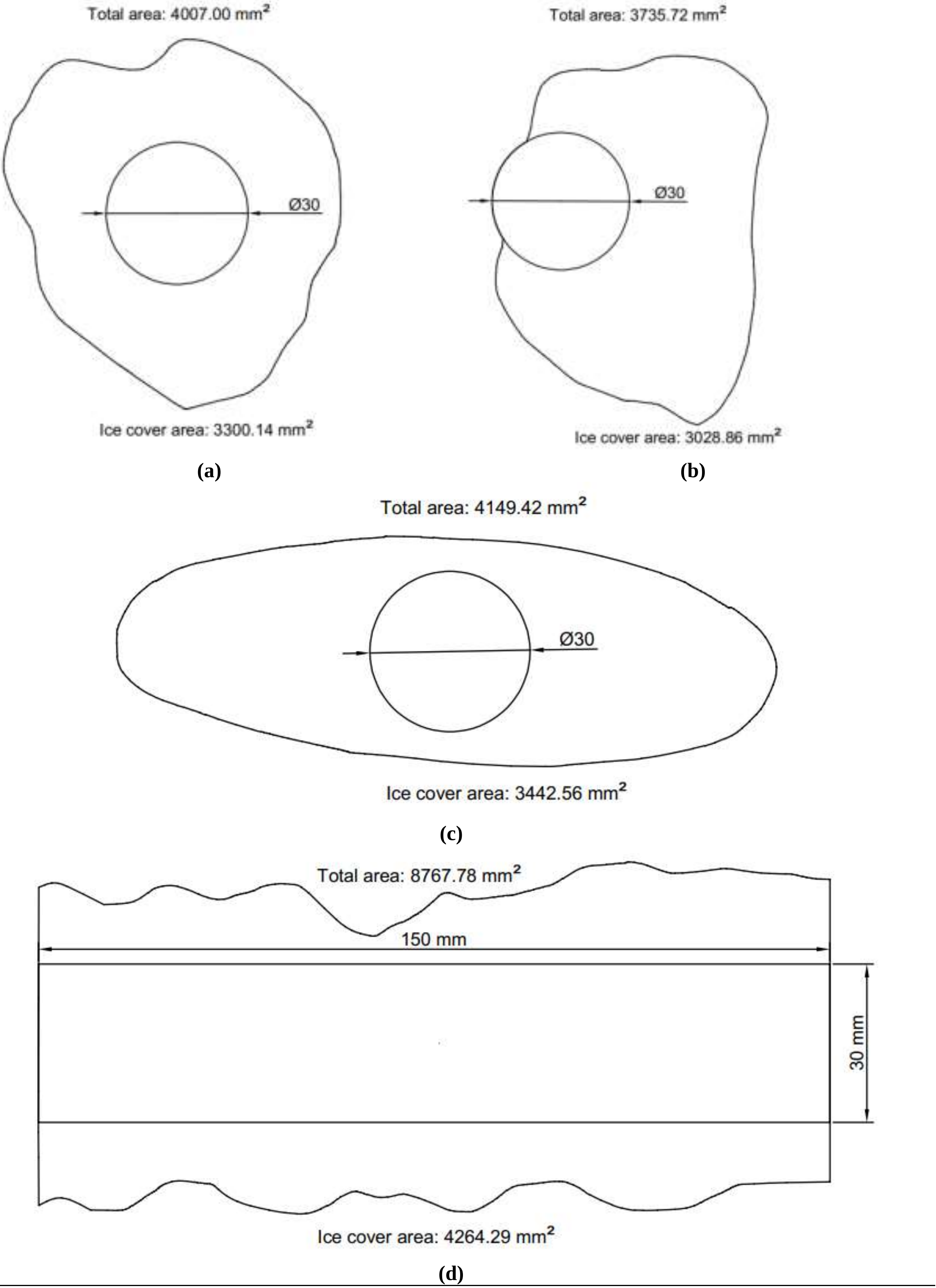
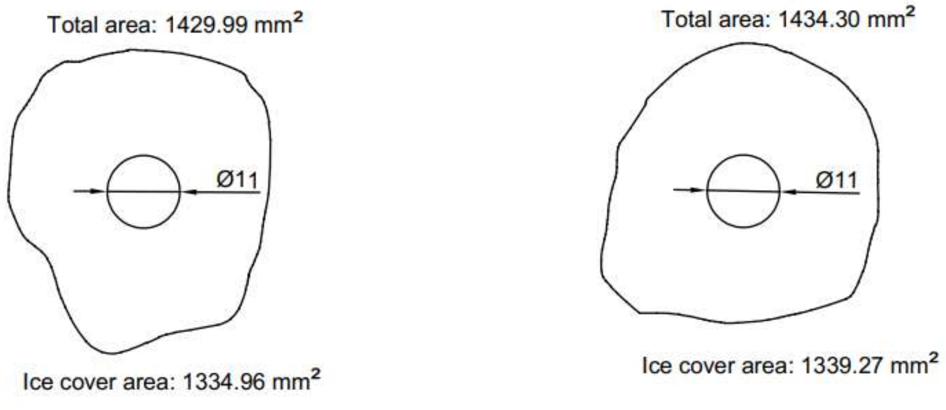


Figure 3 *Cross-sections of the non-cylindrical ice loads in the phases (a,b,c) and lateral field (d)*



(a) **(b)**

Figure 4 *Cross-sections of non-cylindrical ice loads in double protection wires (a, b)*

Table 1 *Values of the defined quantities of non-cylindrical icing*

Values	Figure 1 (a)	Figure 1 (b)	Figure 1 (c)	Figure 1 (d)	Figure 2 (a)	Figure 2 (b)
ε	-	0.26	-	-	-	-
υ (%)	–12.7	–9.6	–14.2	-	3	2.8
σ	1.32	-	1.33	-	0.88	0.9
α (%)	-	-	194.4	-	-	-
β (%)	-	-	–66	-	-	-
γ (%)	16.4	-	98.6	-	10.8	4.3
λ_a (%)	-	-	-	-	0.16	-
λ_b (%)	-	-	-	-	-	0.16
F_b'/F_b	-	-	-	3.35	-	-

with asymmetrical icing. These unstable movements in phase conductors may cause phase-to-phase or phase-to-ground faults. The solution methods for such problems are beyond the scope of this study. Ice load on the transmission line increases the stress on the poles and conductors and weakens the foundations of the poles over time. Power transmission lines are the lifelines of power systems; it is crucial to maintain the functionality of power systems and prevent any possible damage by considering the social and economic aspects of electrical energy. In addition to the analysis and calculations, the power system's operation must continuously and reliably access information from the grid and continually monitor the transmission line. Power flow or voltage problems may indicate that there is a problem in the power lines due to ice load. For this purpose, fixed sensors installed on the transmission system or mobile sensors can be used. While a ground-up installation for the existing power grid is difficult and costly, different methods exist to detect snow load instantaneously. For example, helicopters or drones with the necessary equipment could be helpful. In this way, solutions that are fast, economical, and do not require any contact with the existing electricity system can be developed. However, the weather must be clear and not too windy to carry out such operations. A drone or UAV (Unmanned Aerial Vehicle) would be more cost-effective than a helicopter. UAVs equipped with laser scanners, cameras, and aviation security systems can be used for long-distance monitoring. Data obtained with advanced imaging techniques can be used for ice load analysis using image processing methods.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Author contributions:** The authors declare that they have equal right on this paper.
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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