Renewable Energy, Environment, and Power Quality Journal (REE&PQJ)
ISSN:3020-531X
Volume 26, July 2026

On the Formulas Used To Determine Fair Weather Corona Losses in Transmission Line Conductors

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Abstract. Corona losses reduce transmission efficiency while generating environmental noise and signal interference. Furthermore, the associated chemical discharges accelerate component aging, increasing operational and maintenance costs. This paper assesses the accuracy of prevalent corona loss formulas for overhead transmission lines under fair-weather conditions, the dominant weather condition for most power networks. Comparing these analytical models against international experimental data reveals significant discrepancies between predicted and measured losses. These findings emphasize the inadequacy of existing models and the urgent need for more robust predictive models.

Key words. high-voltage, overhead power lines, corona losses, fair weather.

1. Introduction

Corona performance is an important factor to be considered during the design of direct current (DC) and alternating current (AC) overhead transmission lines [1]–[3], specifically when designing extra-high voltage (EHV) and ultra-high voltage (UHV) overhead transmission lines [4]. Corona performance is measured in terms of corona loss, audible noise, electromagnetic interference or ozone generation among others [2]. The energy losses on high-voltage transmission lines vary with the voltage level. In 110 kV lines, Joule losses are the dominant form of energy loss, while in 220 kV and 400 kV lines corona discharge and leakage losses can become substantial, particularly during foul weather and high precipitation conditions. [5].

When the electric field at the surface of the conductors of a transmission line exceeds a critical value, the air surrounding the conductors becomes ionized and a partial electrical breakdown occurs, resulting in self-sustained corona discharges [6]–[8]. These ions are created, move and recombine. The conductive corona region is not spread wide enough to cause total electrical breakdown or arcing to nearby objects [9]. In addition to heating the air surrounding the conductor, corona activity emits broad-spectrum electromagnetic radiation, UV and visible light, acoustic noise and produces chemical reactions. This process causes power loss, thus requiring energy, which is supplied by the power source to which the transmission line is connected. Corona losses are highly dependent on weather conditions and its economic impact is directly related to the cost of energy. Therefore, the generation sector must compensate for corona losses, especially during rainy and snowy weather conditions. According to [10] , the average annual corona losses of well-dimensioned overhead transmission lines should be less than 10% of the ohmic losses, but if the lines are inadequately dimensioned or heavily loaded under adverse weather conditions, the corona losses can be comparable to the ohmic losses. It is important to be able to allocate the various costs to the appropriate sources, and therefore there is a need to develop accurate models to determine corona loss [11].

As the transmission voltage increases, the conductor diameter must be increased to limit the conductor surface electric field, which is directly related to corona loss [12]. This generally results in conductor cross sections that are larger than those required to limit current density. These conflicting requirements can be met by using bundled conductors [11].

A highly non-uniform electric field distribution is generated around the conductors as a result of the applied voltage [13], with the highest electric field on the surface of the conductors. When the conductors are operated at voltages below the corona inception threshold, a capacitive current flows between the conductors and ground, shifted by 90˚ with the voltage. Due to the resistance of the conductors, this capacitive current produces almost negligible ohmic loss. However, corona discharges occur at voltages greater than the corona inception value, so the oscillatory motion of ions and electrons around the conductors caused by the corona discharges generates an additional current component that is in phase with the voltage and superimposed on the capacitive current that generates the corona loss [14].

For an informed economic selection of conductors of a new transmission line it is very important to know the corona loss characteristics of different conductor models and bundle configurations for a wide range of weather conditions. However, it is very difficult to obtain this information from theoretical calculations due to the complexity of corona discharges, so accurate experimental data is crucial for the development of corona loss methods of high-voltage transmission lines. This measurement is complex since the corona current component is very small compared to the capacitive component and the amount of corona loss is very small compared to the power transmitted by the line [11]. Due to the difficulty of directly measuring corona losses, it is important to have accurate methods for predicting corona losses over a wide range of operating and weather conditions.

Corona losses are challenging to predict due to their dependence on numerous factors, including operating parameters (voltage and frequency), atmospheric conditions (air density, local temperature, and humidity), conductor properties (radius, number, and arrangement of conductors) and surface condition (stranded vs. smooth, presence of dirt, insects, or debris). For example, the maximum surface voltage gradient on a stranded conductor can be approximately 40% greater than that on a smooth conductor of the same diameter [15]. These factors influence the critical corona inception voltage V_c. When the maximum conductor voltage exceeds V_c, corona losses occur. According to the original Peek formulation [16], these losses increase proportional to the square of the difference between the phase voltage and the critical inception voltage, $(V_{phase} - V_c)^2$. Therefore, when transmission lines are operated at low load levels, line overvoltage tends to occur, exacerbating corona losses due to the higher operating voltage [17]. The permissible surface voltage gradient of overhead conductors for transmission lines, is in general is limited below 19 kVrms/cm [18].

In identifying a major gap in high-voltage engineering, the paper highlights that existing formulas are often unreliable and lack general applicability. It shows large discrepancies between predicted and measured losses, with no single model performing consistently across all analyzed configurations. The study compares published formulas, finding EDF best for 765 kV four-conductor bundles, Peek for 330 kV two- and three-conductor bundles, and Tihodeev for single-conductor corona cage simulations. It also highlights missing critical data in literature, such as conductor details, surface irregularities, and local weather conditions. Finally, it must be emphasized that fair weather losses are dominant over time and especially significant for UHV systems due to cumulative yearly energy costs.

2. Corona Losses in Fair Weather

According to IEEE Std. 539 [19], fair weather corresponds to a state of dry conductors due to the absence of precipitation. Contrarily, foul weather corresponds to a weather condition in which the conductors are wet and/or there is precipitation.

Fair weather corona is stable and predictable, depending mainly on air density and conductor surface condition (roughness, contamination). While instantaneous foul weather losses are drastically higher, the sheer duration of fair weather means its low and continuous loss rate contributes substantially to the total annual energy budget, often dictating the baseline loss for the majority of the year. Therefore, the prevalence of fair weather is crucial, particularly for Ultra High Voltage (UHV) systems, where even minor continuous losses accumulate into significant annual power consumption.

Corona losses on transmission lines operating above 230 kV are typically much lower during fair weather than during foul weather conditions such as rain, snow, or hoar-frost. Since fair weather conditions predominate over the course of a year, the calculation of fair weather corona loss is of particular importance. Fair weather corona losses reported in the literature vary widely, ranging from approximately 0.14 W/m/conductor [20] to over 2.0 W/m/conductor [21], [22].

Corona losses present an inverse variation with the radius of the conductors and the distance between conductor centers [23]. In an early paper, Peek [16] proposed an empirical formula to determine the corona loss for smooth, clean and dry conductors, stranded or not stranded under AC supply, which has been largely applied in the literature and can be expressed as [1],

$$P = \frac{241 \cdot 10^{-5}}{\delta} \cdot (f+25) \cdot \sqrt{\frac{r}{S}} \cdot \left(\frac{V_{line,rms}}{\sqrt{3}} - 21.1 \cdot m \cdot \delta \cdot r \cdot \ln(S/r) \right)^2 \ [\frac{\text{kW}}{\text{km} \cdot \text{phase}}] \quad (1)$$

where P [kW/km/conductor] is the corona loss, r [cm] is the radius of the conductor, S [cm] is the average phase spacing, f [Hz] is the power frequency, δ[–] is the relative air density, $m \in [0,1]$ is the dimensionless surface irregularity factor of the conductor, and V_{line} [kVrms] is the line voltage. Note that (1) is dominated by the term $[V_{line,rms}/\sqrt{3} - 21.1 m\delta r \ln(S/r)]^2$, so as r increases, corona losses decrease. It is noted that (1) tends to provide too high corona losses for small conductors and too low corona losses for large conductors [11].

It is well known that the results given by (1) are inaccurate when the AC line is operated close to the corona inception voltage and when the conductors are too large or too small. Peterson's empirical equation refines Peek's original approach to achieve greater precision at low corona loss levels for determining fair-weather corona losses [24]–[26],

$$P = \frac{0.0000209}{\left[\log_{10}(GMD/r)\right]^2} \cdot f \cdot \left(\frac{V_{line,rms}}{\sqrt{3}} \right)^2 \cdot F(E/E_c) \ [\frac{\text{kW}}{\text{km} \cdot \text{phase}}] \quad (2)$$

where GMD [cm] is the geometric mean distance between the phase conductors and $F(E/E_c)$ is a function that depends on the ratio of the maximum surface electric field of the conductors E [kVrms/cm] to the corona inception voltage gradient $E_c = 21.1 \cdot m \cdot \delta \cdot (1 + 0.301/\sqrt{\delta r})$ [kVrms/cm] (see Fig. 1). According to [25], (2) gives accurate results when the ratio E/E_c is close to 1.3. Because (2) neglects air density and bundled configurations, its application is confined to single-conductor lines [11].

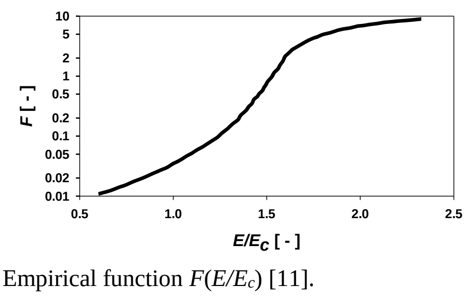

Fig. 1. Empirical function $F(E/E_c)$ [11].

Since (1) and (2) do not apply to lines with bundled conductors, several approaches have been used. Some authors have proposed a modification of the Peek equation that can be applied to AC lines with bundled conductors [27] with n sub-conductors,

$$P = \frac{0.00241}{\delta}(f+25)\sqrt{\frac{r}{GMD}}\left(\frac{V_{line,rms}}{\sqrt{3}} - 21.1 \cdot m \cdot \delta \cdot r \cdot n \cdot \ln(GMD/r)\right)^2 \;\left[\frac{\text{kW}}{\text{km}\cdot\text{phase}}\right] \quad (3)$$

In [11], [28] a similar formula to (3) is proposed,

$$P = \frac{0.00241}{\delta}(f+25)\sqrt{\frac{r}{GMD}}\left[\ln(GMD/r)(E_s - E_c)r\right]^2 \;\left[\frac{\text{kW}}{\text{km}\cdot\text{phase}}\right] \quad (4)$$

where $E_c = 21.1 \cdot m \cdot \delta \cdot (1 + 0.301/\sqrt{\delta r})$ [kVrms/cm] is the corona inception voltage gradient calculated with m = 1 and δ = 1 [11].

Electricité de France (EDF) developed an empirical formula based on based on experimental data from outdoor test cages and space charge considerations that can be applied in fair weather for single and bundle conductors transmission lines as [29],

$$\begin{cases} P = P_0 \cdot r^{1.8} \cdot (n+6)^2 \;\; [\text{kW/km}] \\ \text{New or dirty conductors: } P_{0,\max} = 10^{(-6.6994 + 7.1448 \cdot E_{\max}/E_c)} \\ \text{Clean or aged conductors: } P_{0,\min} = 10^{(-7.8842 + 7.2835 \cdot E_{\max}/E_c)} \end{cases} \quad (5)$$

where r [cm] is the radius of the conductor, n is the number of conductors in each bundle, E_{max} [kVrms/cm] is the maximum value of the electric field of the conductor surface or bundle, and E_c [kVrms/cm] is the corona inception voltage gradient obtained with m = 1 and δ = 1. Note that (5) allows estimating the maximum and minimum corona losses under fair weather conditions, where the minimum losses correspond to clean or aged conductors and the maximum to new or dirty conductors.

A formulation to determine corona losses of heavily contaminated conductors is presented in [30] based on laboratory work using artificially contaminated ACSR conductors.

$$\begin{cases} P(dB) = -a_1 + a_2 \cdot \log_{10}(E_{\max}) + a_3 \cdot \log_{10}(2 \cdot r) \\ \qquad - a_4 \cdot \log_{10}(m) \;\; [\text{dB above 1kW/km}] \\ P = 10^{P(dB)/10} \;\; [\text{kW/km}] \\ \text{Single conductors: } \begin{cases} a_1 = 59.8,\; a_2 = 42.5 \\ a_3 = 19.7,\; a_4 = 21.9 \end{cases} \\ \text{Two-conductor bundles: } \begin{cases} a_1 = 71.7,\; a_2 = 46.7 \\ a_3 = 23.0,\; a_4 = 33.2 \end{cases} \end{cases} \quad (6)$$

where P(dB) is the corona loss expressed in dB above 1 kW/km, P is the corona loss expressed in kW/km, E_{max} [kVrms/cm] is the maximum voltage gradient on the surface of the conductor, r [cm] is the radius of the conductors and m [–] is the surface irregularity factor. Note that (6) can be applied for low values of m and for the range of conditions used in the study, i.e. single ACSR conductors with radius 1.3 – 2.3 cm and two conductor bundles with radius 1.1 – 1.3 cm and values of m $\in$ [0.2,0.8].

In [31] it is proposed to calculate the three-phase corona losses from Tihodeev's formulation [32] as,

$$P = 3 \cdot A \cdot V_{c,phase-n}^2 \cdot e^{B \cdot [(V_{phase-n}/V_{c,phase-n}) - 0.5]} \cdot 10^{-6} \;\; [\text{kW/km}] \quad (7)$$

where $V_{phase-n}$ [kVrms] is the measured phase-to-neutral voltage, $V_{c,phase-n} = E_0 \cdot m \cdot \delta \cdot r \cdot \ln(s/r)$ [kVrms] [12], [33] is the corona inception voltage measured phase-to-neutral, which depends on line design, conductor configuration and surface condition, B = 9.1 and A is a weather dependent coefficient, where in the case of fair weather A = 0.5 [31], and increase for bad weather conditions (dry snow A = 1.4, rain A = 4.3, wet snow A = 6.2, hoarfrost A = 17.5) [34].

BPA proposes a simple approach to determine the corona losses for each conductor as follows [1], [11], [28],

$$\begin{cases} P(dB) = 14.2 + 65\log(E_s/18.8) + 40\log(2r/3.51) + \\ \qquad + K_1 \log(n/4) - 17 \;\; [\text{dB above 1kW/km}] \\ P = 3 \cdot 10^{P(dB)/10} \;\; [\text{kW/km}] \\ K_1 = 13 \text{ for } n \le 4 \text{ and } K_1 = 19 \text{ for } n > 4 \end{cases} \quad (8)$$

Total corona losses (8) must be multiplied by three phases and the sub-conductors per phase.

Other formulations for corona losses were excluded from this work because they rely either on empirical factors tied to specific geometric configurations (e.g., [35], based on [7]) or are only valid for specific voltage levels or require line parameters that are unavailable in practice [36].

Existing corona models for single conductors lack proven applicability to bundled versions; the total loss of n bundled conductors may not simply equal n times that of a single equivalent conductor [36].

Corona losses and inception gradients are sensitive to surface electric fields, conductor conditions, and meteorology. However, current data often omits important details such as specific stranding parameters, line geometry (height and sag), and precise weather variables (solar radiation and wind) required to build robust, universal predictive models.

3. Comparison of Fair Weather Corona Losses in Power Lines

This section compares experimentally measured corona losses in transmission lines with those predicted by the formulas summarized in Section 2.

Table I shows the parameters of three 765 kV overhead transmission lines with bundles of four conductors and horizontally spaced phases, as well as the measured corona losses in fair weather, as presented in [20].

Table I. Experimental data presented in [20] for a 765 kV four-conductors bundle horizontally spaced phases

Conductor diameter [cm]	E_c [kVrms/cm]	$E_{min/max}$ [kVrms/cm]	h [m]	Phase spacing [m]	n	d [cm]	Measured P_c [kW/km]
2.54	26.75	22.7–24.1	12.2	13.7	4	45.7	8.1–18.7
3.04	26.25	19.5–21.0	12.2	13.7	4	45.7	0.63–1.87
3.51	25.95	18.4–17.2	12.2	13.7	4	45.7	0.63–1.87

h: height of the conductor above ground level; d: subconductor spacing

The critical field is obtained from $E_c = 21.1 \cdot m \cdot \delta \cdot (1 + 0.301/\sqrt{\delta r})$ [kVrms/cm] with m = δ = 1 [11]. Table II shows how the formulas summarized in Section 2 compare to the measurements presented in [20] when applied to conductors with the main parameters shown in Table I. As shown in Table II, the results demonstrate the dispersion of the results provided by the different formulas. In this case, however, the EDF formula given by (5) is the most accurate.

Table II. Calculated values using data in [20] for a 765 kV four-conductors square bundle And Conductor height 12.2 m.

	Corona losses, P_c [kW/km]						
Conductor diameter [cm]	Peterson (2)	Peek (4)	EDF (5)	Momb. (6)*	Tihodeev (7)	BPA (8)	Measured P_c [kW/km]
2.54	1.67	24.95	**7.32**	12.38*	17.68	1.49	**8.1 – 18.7**
3.04	1.29	5.24	**1.81**	9.52*	15.11	1.20	**0.63 – 1.87**
3.51	1.09	0.17	**0.51**	7.75*	13.38	1.01	**0.63 – 1.87**
	Relative errors between the formulas and experimental (p.u.)						
2.54	0.8/0.9	-2.08/-0.33	0.10/0.61	-0.5/0.3	-1.2/0.1	0.8/0.9	-
3.04	-1.1/0.3	-7.3/-1.8	-1.9/0.03	-14/-4	-23/-7	-0.9/0.4	-
3.51	-0.7/0.4	0.7/0.9	0.2/0.7	-11/-3	-20/-6	-0.6/0.5	-

*Only valid for n = 1,2

(2) and (4) Calculated with E = mean(E_{min},E_{max}) from Table I

Table III shows the parameters and experimental corona losses of two 330 kV lines: one old line with a bundle of two subconductors and one new line with a bundle of three subconductors per phase. These data can be found in references [37], [38].

Table III. Experimental data presented in [37], [38] for a 330 kV two- and three-conductors bundle

Conductor diameter [cm]	E_c [kV$_{rms}$/cm]	E_{max} * [kV$_{rms}$/cm]	h [m]	Phase spacing [m]	n	d [mm]	*Measured* P_c [kW/km]
2.8 (old)	26.47	14.60	19.75	8.43	2	400	1.0
2.76 (new)	26.51	11.21	21.80	10.00	3	400	1.2

*Obtained with FEA simulations

Table IV shows how the formulas summarized in Section 2 compare to the measurements presented in [37], [38] when applied to conductors with the main parameters shown in Table III. Note that formulas (2) and (4) in Table IV were calculated using FEA simulations, resulting in an average surface voltage gradient of E_{mean} = 8.83 kVrms/cm (old line) and $E_{s,mean}$ = 6.46 kVrms/cm (new line).

Table IV. Calculated values using data in [37], [38] for a 330 kV two- and three-conductors bundle horizontally spaced phases

	Corona losses, P_c [kW/km]						
Conductor diameter [cm]	Peterson (2)	Peek (3)	EDF (5)	Momb. (6)*	Tihodeev (7)	BPA (8)	Measured P_c [kW/km]
2.8 (old)	0.08	0.57	0.02	0.16	0.69	< 0.01	1.0
2.76 (new)	0.04	1.14	<0.01	0.04	0.30	< 0.01	1.2
	Relative errors between the formulas and experimental (p.u.)						
2.8 (old)	0.92	0.43	0.98	0.84	0.31	>0.99	-
2.76 (new)	0.97	0.05	>0.99	0.97	0.75	>0.99	-

*Only valid for n = 1,2

The results summarized in Table IV show the dispersion of results provided by the different formulas, although in this case the Peek formula given by (3) is the most accurate one. The wide discrepancy among the results derived from the analytical formulations summarized in Section 2 clearly demonstrates an inconsistency in formulas used to calculate corona losses for bundled conductors. This is consistent with the reported data in [20].

4. Comparison of Fair Weather Corona Losses in a Corona Cage

Corona cages are essential laboratory tools that simulate the intense electric fields found on overhead transmission lines, eliminating the need for kilometers of actual conductor. For a cylindrical corona cage with a coaxial, round inner conductor, the electric field at the conductor's surface, E_s [kV/cm], can be calculated as [39],

$$E_s = U / [r \cdot \ln(R/r)] \text{ [kV/cm]} \tag{9}$$

where U [kV] is the voltage applied to the conductor, r [cm] is the radius of the conductor and R [cm] is the radius of the cylindrical cage.

Fig. 2 shows the experimental results in a cylindrical corona cage (r = 1.6 cm and R = 50 cm) at different voltage levels, which correspond to different surface electric field strengths.

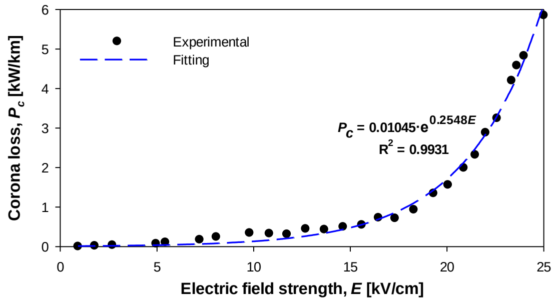

Fig. 2. Corona loss versus the surface electric field [39] and fitting curve.

Table V summarizes the data found in [39] corresponding to different voltages applied to the conductor placed inside the cylindrical corona cage.

Table V. Experimental data presented in [39] for a corona cage (r = 1.6 cm and R = 50 cm) under different applied voltages no bundle (single conductor in a cage)

Conductor diameter [cm]	E_c* [kVrms/cm]	$E_{min/max}$ [kVrms/cm]	P_c exp. [kW/km]
3.2	27.68	5	0.04
3.2	27.68	10	0.13
3.2	27.68	15	0.48
3.2	27.68	20	1.71

*Calculated with the Peek's formula $E_c = 22.3 \cdot \delta \cdot (1 + 0.305/\sqrt{\delta r})$ for concentric cylinders [40], [41] with Uc = 152.42 kVrms.

Table VI shows how the formulas summarized in Section 2 compare to the measurements presented in [39].

Table VI. Calculated values using data in [39] for a corona cage (r = 1.6 cm and R = 50 cm) under different applied voltages no bundle (single conductor in a cage)

	Corona losses, P_c [kW/km]						
E [kV/cm]	Peterson (2)	Peek (4)*	EDF (5)	Momb. (6)**	Tihodeev (7)	BPA (8)	Exp.
5	< 0.01	532.37	< 0.01	0.01	**< 0.01**	< 0.01	0.04
10	0.01	210.50	< 0.01	0.23	**0.02**	< 0.01	0.13
15	0.04	35.33	0.01	1.54	**0.29**	0.03	0.48
20	0.10	6.87	0.27	5.90	**2.63**	0.22	1.71
	Relative errors between the formulas and experimental (p.u).						
5	>0.75	-13308	>0.75	0.75	>0.75	>0.75	-
10	0.92	-1618	>0.92	-0.77	0.85	>0.92	-
15	0.92	-72.60	0.98	-2.21	0.40	0.94	-
20	0.94	-3.02	0.84	-2.45	-0.54	0.87	-

*(4) does not apply because in this configuration the GMD is not defined

** Only valid for n = 1,2

The results summarized in Table VI again show the dispersion of results provided by the different formulas, although in this case the Tihodeev formula given by (7) is the most accurate one.

4. Conclusion

Corona loss represents an energy drain from the system. In EHV/UHV lines, these losses can become substantial and continuous, leading to a measurable reduction in the overall transmission efficiency. Inaccurate loss estimation leads to inaccurate economic planning. Underestimating losses means less power is delivered than expected, resulting in lost revenue. Corona losses are highly sensitive to operating voltage. Even small increases beyond the inception threshold result in a significant increase in power dissipation. Overestimating losses may lead to unnecessarily conservative (and thus expensive) design choices.

This paper has made evident that despite there are many formulations to determine corona losses in power lines, experimental data shows that these formulas exhibit a great variability in the results, so they are not reliable and are not generalizable for different power line configurations. The lack of accuracy of these formulas is not due to a single flaw, but rather a combination of how they simplify complex physics and their reliance on specific historical datasets. These limitations emphasize the need to replace existing models with more robust predictive models.

Classical formulas like Peek and Peterson were developed for single conductors and do not reliably extend to bundled systems, where electric fields are highly non-uniform. It is unproven that bundle losses equal the sum of individual sub-conductors, and simplified adaptations often fail to capture their interactions. A major error source is the surface irregularity factor *m*, typically estimated rather than measured, causing large prediction variability. Additionally, most models ignore that stranded conductors can have up to 40% higher surface voltage gradients than smooth ones, significantly affecting corona losses. Since corona is extremely sensitive to electric field variations, small parameter inaccuracies such as field ratios, conductor height, voltage, or air density, can lead to large errors in corona loss predictions.

Improved formulations could explore exponential or power-law structures as $P_c = k \cdot \delta^a \cdot f^b \cdot n^c \cdot r^d \cdot e^{\alpha \cdot E_{\max}/E_c}$. Reliable corona loss models for power lines are essential for cost-benefit analysis and accurate annual energy loss prediction. The lack of reliable formulations means that engineers must rely on expensive, time-consuming experimental tests or models that introduce significant uncertainty. Establishing new, physics-based, and empirically validated models that accurately account for the complex electric field of bundled conductors and the variable environmental factors is paramount for ensuring the high reliability, efficiency, and cost-effectiveness of modern, high-power transmission grids.

Acknowledgement

This project received funding from grant PID2023-147016OB-I00, by MICIU/AEI/https://doi.org/10.13039/501100011033/ and by ERDF "A way of making Europe," by the European Union and from the Agència de Gestió d'Ajuts Universitaris i de Recerca-AGAUR (2021 SGR 00392).

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