From Flash Density to Field Reliability: A Population-Weighted Distance Effect Model for Lightning-Induced Surge Exposure Characterization

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Abstract—*Lightning-induced surge voltages constitute a primary failure mechanism for outdoor electronic equipment deployed in residential and commercial environments. This paper presents a physics-based Distance Effect model that establishes the quantitative relationship between lightning-induced voltage magnitude and the spatial volume fraction capable of producing that voltage level, yielding an inverse cubic law ($O \propto U_i^{-3}$, where O denotes the spatial occurrence ratio and Ui the induced voltage magnitude). The model derives from the classical Rusck formulation with correction factors for finite conductor length and structural shielding, and is subsequently integrated with regional lightning density data and population distribution analytics to develop a generalized, data-driven framework for surge exposure characterization. Utilizing 2024 U.S. National Lightning Detection Network data across all 50 states, the paper demonstrates the application of this framework through population-weighted analytical calculations. The methodology transforms surge analysis from empirical estimation into a rigorous, physics-backed analytical approach, providing a generalizable methodology for surge exposure characterization applicable across diverse deployment scenarios. Validation against IEEE C62.41.1 empirical data confirms the model's predictive accuracy, while the population-weighted aggregation methodology demonstrates how spatial occurrence models can be combined with demographic data to produce representative national-scale characterizations.*

Keywords—lightning-induced voltage modeling, distance effect model, inverse cubic occurrence law, population-weighted analysis, surge exposure characterization, geographic lightning variability, lightning density

I. INTRODUCTION

A. Problem Statement and Motivation

Outdoor electronic equipment faces fundamentally different lightning exposure profiles compared to indoor devices. While building-level surge protection infrastructure shields indoor products, outdoor terminals—including satellite communication devices, outdoor security cameras, and distributed Internet of Things (IoT) sensors—experience direct coupling to overhead power and communication lines during lightning events. The absence of quantitative, physics-based frameworks for characterizing the relationship between lightning activity and surge voltage occurrence across geographic regions has limited the ability to systematically analyze surge exposure for outdoor installations in this environment category.

The challenge intensifies when considering geographic variability in lightning activity. Florida experiences 91.4 flashes per square kilometer per year, whereas California records only 0.6 flashes per square kilometer per year—a 152-fold difference. Traditional compliance-based approaches, which apply uniform test levels regardless of deployment location, lack a quantitative physical basis linking geographic lightning variability to expected surge voltage distributions.

B. Research Gap and Contribution

Existing lightning protection standards, including IEC 61000-4-5 [1] and IEEE C62.41.1 [2], provide test methodologies and exposure categories but lack quantitative frameworks linking surge voltage thresholds to spatial occurrence outcomes. The Rusck model establishes voltage-distance relationships for infinite conductors in open terrain [3], yet practical applications require correction factors for finite cable lengths and structural shielding effects. Furthermore, no prior work has integrated spatial occurrence probability with population distribution to derive representative exposure characterizations.

This paper addresses these gaps through three contributions. First, a corrected Distance Effect model relating induced voltage to spatial occurrence ratio via inverse cubic relationship ($O \propto Ui-3$), where O represents the fraction of the total exposure volume within which a given voltage level can be induced. Second, a demonstration of the framework's application through regional analysis integrating 2024 National Lightning Detection Network data with population distribution analytics. Third, a population-weighted aggregation methodology that illustrates how spatial occurrence models can be combined with demographic data to produce representative national-scale characterizations.

C. Scope and Theoretical Implications

The derived analytical framework contributes to the theoretical understanding of lightning-induced surge exposure by establishing quantitative relationships between physical parameters and occurrence statistics. While the framework may inform practical applications such as surge protection design and insulation coordination, the primary contribution is the analytical methodology itself. Accurate characterization of the surge environment is essential for any subsequent engineering application, and the theoretical framework developed herein provides the quantitative basis upon which such characterizations can be constructed. The population-weighted approach demonstrates how theoretical occurrence models can be contextualized through demographic weighting to reflect actual exposure distributions across a user population.

II. THEORETICAL FOUNDATION: DISTANCE EFFECT MODEL

A. Physics-Based Voltage-Distance Relationship

The foundational relationship derives from the Rusck model for lightning-induced voltages on overhead conductors [3]. For a vertical lightning channel carrying current I at horizontal distance r from a conductor of height h_c, the induced voltage U_i follows:

$$U_i = (\alpha_{\text{eff}} \times h_c \times I) / r \tag{1}$$

where α_{eff} represents the effective coupling coefficient, accounting for finite line length and structural shielding effects. The classical Rusck formulation assumes infinite conductor length in open terrain, yielding $\alpha \approx 25$. Practical outdoor terminal installations, however, involve cable runs restricted to 30–50 m, significantly below the critical coupling length of approximately 300 m for typical lightning rise times.

Andreotti et al. demonstrated through exact analytical solutions that induced voltage magnitude exhibits strict dependence on conductor length [4], with numerical simulations by Ahmad et al. confirming effective coupling efficiency of 10–30 percent for short cable runs [5]. This physical truncation of the integration path necessitates a length correction factor $K_{\text{Length}} = 0.3$. Structural shielding introduces additional attenuation. Outdoor terminals typically mount on grounded metal brackets or route along conductive walls, creating mutual inductance cancellation as quantified in IEEE Std 1410-2010 [6]. The standard specifies shielding factors of 0.3–0.5 for lines protected by nearby objects. Adopting a conservative $K_{\text{Shielding}} = 0.4$, the effective coupling coefficient becomes:

$$\alpha_{\text{eff}} = \alpha_{\text{theoretical}} \times K_{\text{Length}} \times K_{\text{Shielding}} = 25 \times 0.3 \times 0.4 = 3 \tag{2}$$

For typical residential and commercial overhead line height $h_c = 10$ m and median lightning current $I = 10$ kA [7], Eq. (1) simplifies to:

$$U_i = 300{,}000 / r \tag{3}$$

with U_i in volts and r in meters.

B. Geometric Occurrence Ratio Framework

Lightning strikes occur randomly within three-dimensional geographic space. The occurrence ratio associated with a lightning event inducing a specific voltage level is proportional to the spatial volume within which that voltage can be generated. Since induced voltage decreases with distance per Eq. (3), higher voltage events can only occur within smaller radii around the strike point.

Lightning occurrence O is defined as a volume ratio. Specifically, it is the ratio of the hemispherical volume within which lightning events can induce a voltage equal to or exceeding U_i, to the total hemispherical exposure volume bounded by R_{boundary}:

$$O(U \geq U_i) = V(r \leq r_{\max}) / V_{\text{total}} = [(2/3)\pi r_{\max}^3] / [(2/3)\pi R_{\text{boundary}}^3]$$

where $r_{\max} = \alpha_{\text{eff}} \cdot h_c \cdot I / U_i$ is the maximum strike distance capable of inducing voltage $\geq U_i$, and R_{boundary} defines the outer limit of the exposure zone:

$$O = (C / 2) \times (4/3) \times \pi \times r^3 \tag{4}$$

where $C = 1/V_{\text{total}}$ encapsulates the inverse of the total exposure volume, with regional lightning density incorporated in subsequent annual event calculations (Section III), and the factor one-half accounts for hemispherical (not full spherical) distribution above ground. The cubic relationship captures a critical physical insight. As distance from the strike point increases, available space grows as r^3, dramatically increasing occurrence ratio. Simultaneously, induced voltage decreases as $1/r$, creating an inverse relationship between voltage severity and occurrence frequency.

Remark: The term 'occurrence' in this paper refers specifically to a geometric volume ratio under the uniform spatial distribution assumption, not to a temporal frequency. The temporal dimension (annual event count) is introduced separately in Section III through regional lightning density data.

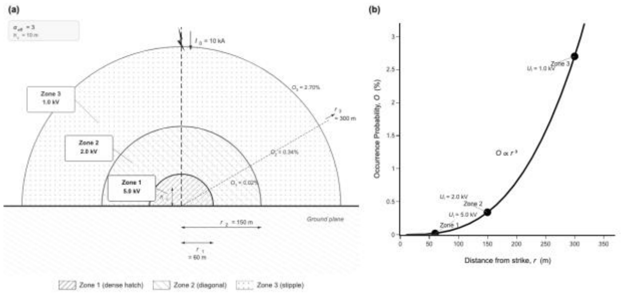

Fig. 1. Spatial distribution model for lightning-induced surge event probability. (a) Cross-sectional schematic of the hemispherical occurrence volume showing three representative zones at distances $r = 60$, 150, and 300 m from the strike point, with corresponding induced voltages of 5.0, 2.0, and 1.0 kV. Hatching density indicates relative occurrence ratio. (b) Spatial occurrence ratio O as a function of distance r, representing the fraction of total exposure volume enclosed within radius r, demonstrating cubic growth ($O \propto r^3$) with zone data points (●) and hemispherical volume equivalents. Parameters: $I = 10$ kA, $\alpha_{\text{eff}} = 3$, $h_c = 10$ m.

C. Derivation of the Ui–O Relationship

Eliminating the distance variable r between Eqs. (3) and (4) establishes the direct relationship between induced voltage and occurrence ratio. From Eq. (3):

$$r = 300{,}000 / U_i \tag{5}$$

Substituting into Eq. (4):

$$O = (C / 2) \times (4\pi / 3) \times (300{,}000 / U_i)^3 = K \times U_i^{-3} \tag{6}$$

where $K = (\alpha_{\text{eff}} \cdot h_c \cdot I)^3 / R_{\text{boundary}}^3$ consolidates the geometric and electromagnetic parameters into a single constant.

The concordance between this theoretical prediction and empirical field measurements is examined in Section IV-B, where the model is validated against IEEE C62.41.1 surge occurrence data [2].

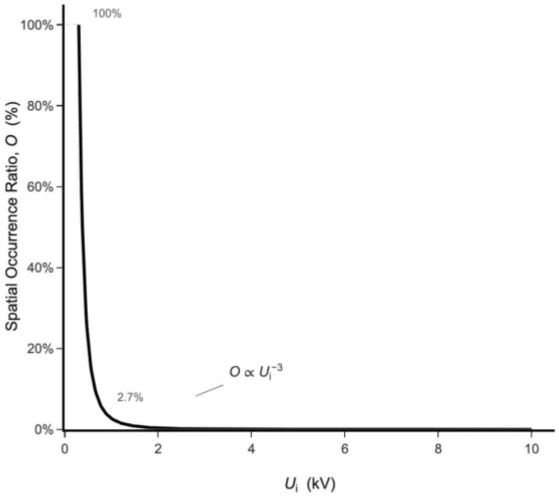

Fig. 2. Spatial occurrence ratio O as a function of induced voltage U_i on a linear scale, showing the U_i^{-3} decay predicted by the Distance Effect model (Eq. 6). The steep descent reflects the inverse cubic relationship: as the voltage threshold increases, the fraction of the total exposure volume capable of producing that voltage diminishes rapidly. The heavy-tail characteristic indicates that low-voltage surge events dominate the occurrence distribution, while high-voltage events are increasingly rare. Parameters: $I = 10$ kA, $\alpha_{\text{eff}} = 3$.

III. FROM OCCURRENCE RATIO TO ANALYTICAL FRAMEWORK

A. Regional Lightning Density Integration

The annual event count n depends on regional lightning activity. Data were obtained from the 2024 U.S. National Lightning Detection Network (NLDN) operated by Vaisala [8], providing annual flash density D for all 50 states in units of flashes per square kilometer per year.

For a point of interest at a specific geographic location, the annual number of lightning events within the exposure zone is:

$$n_{\text{annual}} = D \times A_{\text{impact}} \times f_{\text{CG}} \tag{7}$$

where $A_{\text{impact}} = \pi \times r_{\text{impact}}^2$ represents the impact area, $f_{\text{CG}} = 0.25$ accounts for the cloud-to-ground fraction, and $r_{\text{impact}} = 1$ km is adopted based on IEEE Std 1410-2010 guidance [6], yielding:

$$n_{\text{annual}} = 0.785 \times D \tag{8}$$

B. Single-Event Survival Probability

For a system characterized by a voltage withstand capability of $V_{\text{threshold}}$, the single-event survival probability P_{single} is the complement of the spatial occurrence ratio at that threshold:

$$P_{\text{single}}(V_{\text{threshold}}) = 1 - O(U \geq V_{\text{threshold}}) \tag{9}$$

Substituting the Distance Effect model result (Eq. (6)):

$$P_{\text{single}} = 1 - K \cdot V_{\text{threshold}}^{-3} \tag{10}$$

This equation establishes the fundamental bridge between the spatial occurrence framework (Section II) and the reliability framework developed below. Physically, P_{single} represents the probability that a single random lightning event within the exposure zone induces a voltage below the system's withstand capability.

C. Multi-Event Annual Reliability Model

A system located within the exposure zone experiences multiple independent lightning events per year. Assuming statistical independence between events, the annual reliability R_{annual}—defined as the probability that the system survives all n events in one year without surge-induced failure—follows the binomial survival model:

$$R_{\text{annual}} = (P_{\text{single}})^{\text{n}} \tag{11}$$

Adopting an illustrative reliability assumption of $R_{\text{annual}} \geq 0.995$ (99.5 percent) for demonstration purposes and applying the approximation $\ln(1 - x) \approx -x$ for small x:

$$n \cdot K \cdot V_{\text{threshold}}^{-3} \leq 0.00501 \tag{12}$$

Solving for the corresponding voltage level under this illustrative assumption:

$$V_{\text{threshold}} \geq (n \cdot K / \, 0.00501)^{1/3} \tag{13}$$

Equation (13) explicitly relates the voltage level to the number of annual lightning events n and the geometric-electromagnetic constant K. The cube-root dependence means that the corresponding voltage level scales sub-linearly with event count—doubling the number of events increases the corresponding voltage level by only 26 percent.

Substituting Eq. (8) into Eq. (13) yields the state-specific voltage level as a function of lightning density alone:

$$V_{\text{threshold}}(D) \geq (0.785 \cdot D \cdot K / \, 0.00501)^{1/3} \tag{14}$$

Representative calculations yield: Florida (D = 91.4 fl/km²/yr, n = 71.7 events/yr), $V_{\text{threshold}} = 7.29$ kV; Texas (D = 58.1 fl/km²/yr, n = 45.6 events/yr), $V_{\text{threshold}} = 6.27$ kV; California (D = 0.6 fl/km²/yr, n = 0.5 events/yr), $V_{\text{threshold}} = 1.40$ kV. These values illustrate the model's sensitivity to regional lightning density variation. Complete state-by-state results are presented in Table I.

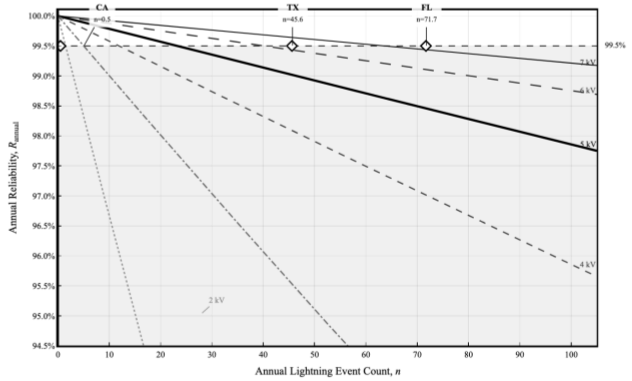

Fig. 3. Annual reliability Rannual as a function of annual lightning event count n for voltage withstand thresholds of 2–7 kV, computed from the binomial survival model Rannual = (Psingle)n (Eq. 11) with Psingle = 1 − K · V−3 (Eq. 10). The dashed horizontal line denotes the 99.5% annual reliability target (Eq. 12). Diamond markers indicate state-level design points for Florida (D = 91.4, n = 71.7), Texas (D = 58.1, n = 45.6), and California (D = 0.6, n = 0.5), each satisfying the reliability constraint at their respective event counts. The shaded region below 99.5% represents unacceptable field failure rates. The sub-linear cube-root dependence Vthreshold ∝ n1/3 is evident from the wide spacing between curves.

D. Population-Weighted National Analysis

A unified national analysis must balance characterization across states with vastly different lightning exposure. Applying uniform geographic weighting would over-represent sparsely populated high-lightning states. Instead, population weighting aligns the analysis with actual user deployment density, maximizing representativeness for the user base.

The population-weighted voltage characterization is defined as:

$$V_{\text{weighted}} = \Sigma_i \left[V_{\text{threshold},i} \times w_{\text{pop},i} \right] \qquad (15)$$

where the population weight for state i is:

$$w_{\text{pop},i} = \text{Pop}_\text{i} \,/\, \text{Pop}_{\text{total}} \quad \text{with} \quad \Sigma w_{\text{pop},i} = 1 \qquad (16)$$

Population data were obtained from Stats America 2024 [9] with $\text{Pop}_{\text{total}}$ = 335,000,000. The population-weighted contribution column in Table I demonstrates the weighting effect: Texas (9.34% weight, 6.27 kV) contributes 0.586 kV; California (11.77% weight, 1.40 kV) contributes 0.165 kV. The calculated population-weighted result yields V_{weighted} = 4.33 kV.

This value of 4.33 kV represents the direct analytical output of the Distance Effect model under the stated assumptions (illustrative 99.5 percent annual reliability criterion, median 10 kA current, $\alpha_{\text{eff}} = 3$). It is presented as a model output for the purpose of demonstrating the framework's capability, rather than as a design specification. Practical application of this framework would require additional consideration of model uncertainties, installation variability, and site-specific factors, which are beyond the scope of this theoretical study.

IV. RESULTS AND VALIDATION

A. State-by-State Analysis

Table I presents comprehensive results for all 50 U.S. states, ranked by lightning density. Applying Eq. (14), the analysis reveals several characteristic patterns. High-lightning states (Florida, Oklahoma, Louisiana, Arkansas, Texas) yield voltage values exceeding 6 kV under the illustrative 99.5 percent annual reliability assumption. Mid-range states (Kentucky through South Carolina) yield 4–6 kV voltage values. Low-lightning states (Oregon, California, Alaska, Washington, Hawaii) yield less than 2 kV voltage values based solely on local lightning exposure.

The population-weighted contribution column demonstrates the weighting effect. Texas, ranked fifth in lightning density, contributes the highest weighted voltage (0.586 kV) due to its 31.3 million population (9.34 percent national weight). California, ranked 48th in lightning density, contributes 0.165 kV despite a local value of only 1.4 kV, reflecting its 39.4 million population (11.77 percent weight). This population weighting ensures that the national characterization is representative of the majority of the user base.

B. Model Validation Against Empirical Data

The Distance Effect model predicts that the spatial occurrence ratio *O* decreases as U_i^{-3} (Eq. (6)). To validate this theoretical prediction, the model is compared against empirical surge occurrence data documented in IEEE C62.41.1 [2], which reports surge occurrence following the "third power law" based on extensive monitoring of low-voltage AC circuits.

Additional validation derives from IEEE Std 1410-2010 field measurements and triggered-lightning experiments [6]. The conservative correction factors ($K_{\text{Length}} = 0.3$, $K_{\text{Shielding}} = 0.4$) provide safety margin against measurement variations.

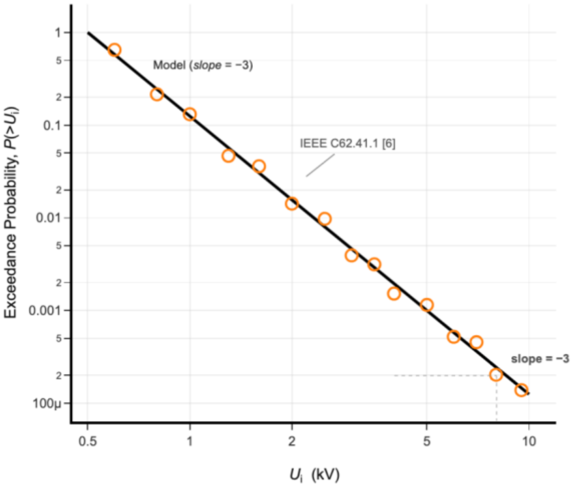

Fig. 4. Empirical validation of the Distance Effect model on a log-log scale. The solid line represents the theoretical exceedance probability $P(>U_\text{i}) \propto U_\text{i}^{-3}$ derived from the spatial occurrence ratio (Eq. 6). Open circles denote field measurements from IEEE C62.41.1 [2], obtained through extensive monitoring of surge events on low-voltage AC circuits. The close agreement between theory and measurement across nearly three decades of voltage confirms the inverse cubic relationship and validates the Distance Effect model as a predictive tool for surge specification. Parameters: I = 10 kA, $\alpha_{\text{eff}} = 3$.

TABLE I. STATE-BY-STATE LIGHTNING RISK ANALYSIS AND VOLTAGE THRESHOLD DETERMINATION

Rank	State	Lightning Density (fl/km²/yr)	Annual Events (events/yr)	Population	Pop. Weight (%)	Required Psingle (%)	Voltage Threshold (kV)	Weighted Contrib. (kV)
1	Florida	91.4	71.7	23,372,215	6.98	99.993	7.29	0.509
2	Oklahoma	75.2	59.0	4,095,393	1.22	99.992	6.83	0.083
3	Louisiana	71.7	56.3	4,597,740	1.37	99.991	6.72	0.092
...	*(41 more states)*		...	...	...	...	...	*3.747*
48	California	0.6	0.5	39,431,263	11.77	99.003	1.40	0.165
49	Hawaii	0.4	0.31	1,440,196	0.43	98.415	1.19	0.005
50	Alaska	0.2	0.16	733,536	0.22	96.858	0.95	0.002
	TOTAL	16.8*	13.2*	335,000,000	100.0	99.500	4.33**	4.33

** Population-weighted average. ** Population-weighted specification. Lightning density from 2024 NLDN* [8]. *Population from Stats America 2024* [9].

C. Analytical Output and Contextual Comparison

The population-weighted analytical output of 4.33 kV (Eq. (15)) can be contextualized against existing standard test levels. This value falls in the range of IEC 61000-4-5 test levels [1], which suggests qualitative consistency between the theoretical framework and established empirical practice. The difference between the model output and standard test levels reflects the distinct exposure conditions of outdoor installations compared to the indoor environments addressed by existing standards, rather than constituting a specific design recommendation.

V. DISCUSSION

A. Theoretical Implications and Potential Applications

The results presented in Section IV demonstrate the practical utility of the population-weighted framework. By combining the Distance Effect model with demographic data, the analysis captures the heterogeneous nature of lightning exposure across the U.S. user base. The analytical framework predicts that installations in Florida (71.7 annual events) experience $P_{\text{single}} = 0.99993$ per event, while installations in California (0.5 annual events) yield $P_{\text{single}} = 0.99001$, illustrating the model's ability to quantify geographic exposure variation.

The theoretical framework has potential implications for safety-related applications. Lightning-induced surge events can lead to component degradation and insulation stress, as documented in ITU-T K.21 [10] and IEEE Std 1410-2010 [6]. The Distance Effect model offers a quantitative basis for characterizing the geographic distribution of such exposure, which may support future safety assessment methodologies.

B. Comparison with Existing Standards

IEC 61000-4-5 defines four surge immunity test levels: Level 1 (0.5 kV), Level 2 (1 kV), Level 3 (2 kV), and Level 4 (4 kV) [1]. The standard provides test methodologies but offers limited guidance on level selection for specific applications. The model output of 4.33 kV falls within the range of existing standard test levels. This correspondence between the independently derived theoretical result and established empirical test levels lends credibility to the Distance Effect model's physical assumptions. The analysis suggests that for high-lightning states, the theoretical voltage characterization exceeds standard Level 4 values, which is physically consistent with the enhanced outdoor exposure conditions not fully addressed by existing indoor-focused standards.

IEEE Std 1410-2010 focuses on distribution line protection [6], yet its induced-voltage flashover calculations provide validation for the Distance Effect model. ITU-T K.21 addresses telecommunication equipment safety [10] but specifies only 1.5 kV for overvoltage category II, which corresponds to a lower exposure category than what the Distance Effect model predicts for outdoor installations with direct line exposure.

C. Model Limitations and Future Work

Several limitations warrant acknowledgment. The model assumes median lightning current (10 kA), whereas actual distributions span 1–200 kA with log-normal characteristics [7]. Extreme events exceeding 50 kA occur with 10 percent probability, potentially inducing voltages beyond model predictions at close distances. Ground resistivity effects, which can enhance induced voltage amplitude by 20–40 percent in high-resistivity soils, are not explicitly modeled. The 99.5 percent reliability assumption adopted in this study is illustrative; different application contexts may warrant different assumptions, and the framework accommodates arbitrary reliability parameters through Eq. (13). Future research directions include extending the model to other geographic regions, incorporating time-varying reliability assumptions, developing probabilistic current amplitude distributions, and validating through field failure data collection.

VI. CONCLUSION

This paper presents a physics-based, population-weighted analytical methodology for characterizing lightning-induced surge exposure for outdoor electronic equipment. The Distance Effect model establishes the quantitative relationship between lightning-induced voltage and spatial occurrence ratio ($O \propto U_i^{-3}$), validated against IEEE C62.41.1 empirical data (Fig. 4). Integration with 2024 U.S. National Lightning Detection Network data and population distribution analytics yields a population-weighted analytical output of 4.33 kV under the stated assumptions (illustrative 99.5 percent annual reliability criterion, median lightning current, corrected coupling coefficient). This result demonstrates the framework's ability to synthesize electromagnetic theory, geographic data, and demographic information into quantitative surge exposure characterizations.

The methodology establishes a physics-based analytical framework that bridges the gap between classical lightning-induced voltage theory and regional-scale surge exposure characterization, with potential applications in electrical safety assessment and reliability analysis. Population weighting ensures that analytical outcomes reflect actual exposure distributions rather than uniform geographic coverage. The framework is extensible to other product categories, geographic regions, and reliability assumptions, providing a generalizable approach for physics-based surge exposure characterization.

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