

Modelling and Analysis of Lightning Protection System Performance in Urban High-Rise Structure

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ABSTRACT

High-rise buildings are particularly vulnerable to lightning strikes in rapidly urbanizing areas due to their height and close proximity to other structures. Reliable Lightning Protection Systems (LPS) are therefore essential for safety and infrastructure resilience. Conventional methods of assessing LPS performance often depend on physical inspections or post-event analysis, which can be time-consuming, limited in scope, and sometimes hazardous. Moreover, existing approaches may not fully capture the complex interaction between lightning discharge behavior and diverse building geometries in dense urban settings. To address these challenges, this study proposes a simulation-based methodology using COMSOL Multiphysics to evaluate LPS performance in urban high-rise buildings. The research models electric field distribution and current flow paths during lightning strikes, allowing detailed analysis of key LPS components such as air terminals, down conductors, and grounding systems. By simulating various strike scenarios, the study identifies critical high-risk zones and supports the optimization of protection design. The expected outcome is a deeper understanding of LPS effectiveness in complex urban environments, contributing to more robust and predictive protection strategies for high-rise structures.

Keywords: COMSOL Multiphysics, Electric Field Simulation, High-rise Buildings, Lightning Protection System, Urban Infrastructure

1. INTRODUCTION

Lightning is a common natural phenomenon that poses a severe threat to tall structures, particularly in regions with high lightning density such as Malaysia. According to Holle [1], Malaysia records approximately 40 lightning strikes per km² annually, which significantly increases the exposure of tall buildings to electrical hazards. The impact of lightning on modern urban structures can result in severe physical damage, fire, and power disruption if not adequately protected by a reliable Lightning Protection System (LPS).

A well-designed LPS minimizes these risks by providing a low-resistance path for lightning current to flow safely into the ground. However, many conventional LPS assessments rely solely on physical inspection or post-strike analysis, which may not accurately represent the actual electromagnetic behavior of the system [2]. Researchers such as Du [2] and Negara et al. [3] have emphasized that purely experimental evaluation of LPS configurations can be time-consuming, costly, and sometimes hazardous. To overcome these challenges, numerical simulation has become an essential alternative for predicting lightning performance in high-rise buildings.

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Simulation tools such as COMSOL Multiphysics are particularly effective for studying the electric-field distribution and potential behavior using the Finite Element Method (FEM) [4]. FEM-based simulation allows researchers to visualize field concentration zones, determine risk points, and evaluate the effectiveness of protection elements before real-world implementation [5]. Several

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studies have utilized FEM in lightning research, including work by Daḡa et al. [4] who modeled electric-field intensities in complex structures, and Rahman et al. [6] who applied similar methods to evaluate current flow in tall buildings.

2. MATERIAL AND METHODS

The simulation was performed using COMSOL Multiphysics 6.2 under the *Electrostatics* interface. The software applies the Finite Element Method to solve Poisson's equation for electric potential in complex geometries [7]. A two-dimensional (2D) vertical cross-section of a 60-storey reinforced-concrete building was developed to replicate the essential physics while minimizing computation time. The building model was equipped with air terminals, down conductors, and a soil grounding region.

2.1 Geometry and Material Properties

Figure 1 shows the geometry of the model building. In the geometry construction stage, a 2D representation of the high-rise structure and its surrounding elements was created. The model included a large air domain to simulate open atmosphere, a rectangular building block to represent the structure, and thin copper rectangles on top of the building to model air terminals (lightning rods). Vertical copper strips were drawn along the building edges to represent down conductors. A soil domain was added beneath the building to simulate the grounding system. All components were modeled as rectangles to ensure compatibility with 2D domain physics and material assignment.

The air region was assigned a relative permittivity of 1. The concrete building was given a relative permittivity of 5 and a conductivity of 0.01 S/m. Copper, used for both air terminals and down conductors, was assigned a high conductivity of 5.96×10^7 S/m without defining permittivity. The soil domain was defined with a relative permittivity of 10 and conductivity of 2 S/m to model the grounding environment. Each material was correctly mapped to its respective domain through the Materials node presents in Table 1.

Table 1. Material properties used in the simulation

Material	Relative Permittivity (ϵ_r)	Conductivity (S/m)
Air	1	-
Concrete	5	0.01
Copper	-	5.96e7
Soil	10	2

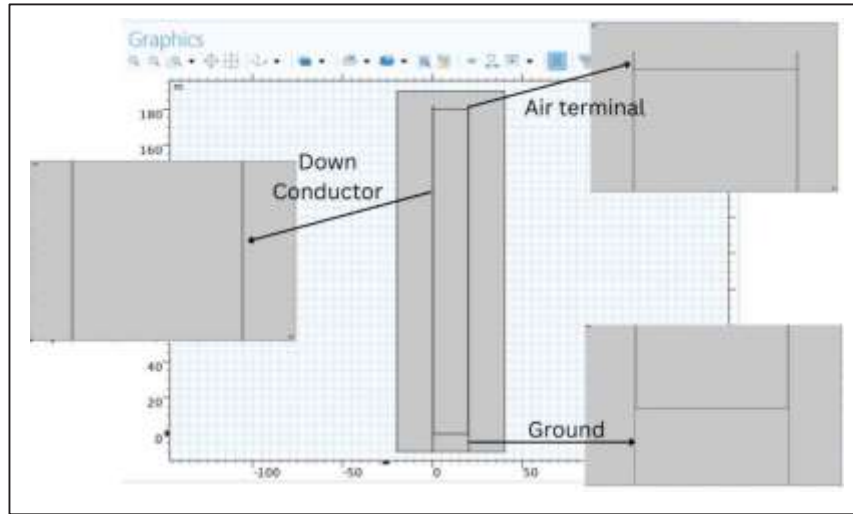


Figure 1. Two-dimensional model building

2.2 Boundary Conditions

As shown by Guo et al. [9], an electric potential of 100 kV was given to the lightning rod's tip to simulate a downward leader approaching the structure. To stop charge leakage, the soil's bottom barrier was grounded at 0 V, and all other external boundaries were electrically insulated.

2.3 Meshing and Solver Settings

A fine triangular mesh was applied to regions near sharp corners such as the rod tip and conductor joints to capture electric field gradients accurately. Rizk [10] investigated lightning exposure of tall structures using similar meshing techniques. The stationary solver used conventional FEM-based computational approaches to calculate both electric potential and electric field.

2.4 Grounding Configuration

Ground rod, ground plate and ground grid were the three grounding configurations that were assessed. To ensure a fair comparison, the same material properties were used to represent each arrangement. Electric field distribution properties and magnitude were used to evaluate performance.

3. RESULTS AND DISCUSSION

3.1 Visual Result

The simulation results were visually presented using COMSOL's postprocessing tools to illustrate the electric field distribution around the high-rise building. Color maps and contour plots were generated to highlight areas of high electric field intensity, particularly near the rooftop and along structural edges. These visuals offer vital information about possible lightning strike locations and aid in assessing how well the LPS design reduces danger.

3.1.1 Electric Potential Distribution

According to the modelling results in Figure 2, the lightning rod tip had the maximum electric potential (100 kV), which smoothly decreased along the down conductor towards the ground. This gradient demonstrates that the lightning energy is effectively diverted from the building surface by the LPS. Negara et al. [4] reported similar potential profiles in comparable evaluations of high-rise protection systems.

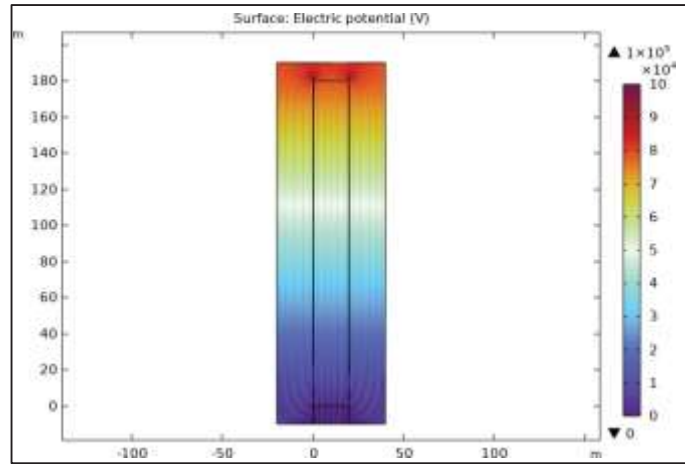


Figure 2. Electric potential distribution along the high-rise building

3.1.2 Electric Field Magnitude

As shown in Figure 3, the maximum electric field magnitude of 1.82×10^6 V/m was observed at the tip of the lightning rod, consistent with results by Dada et al. [6]. This value remains below the air breakdown threshold of 3×10^6 V/m [11], indicating that the LPS design provides adequate protection against dielectric failure. The field intensity along the building façade was approximately 1.2×10^6 V/m, well within safe operating limits.

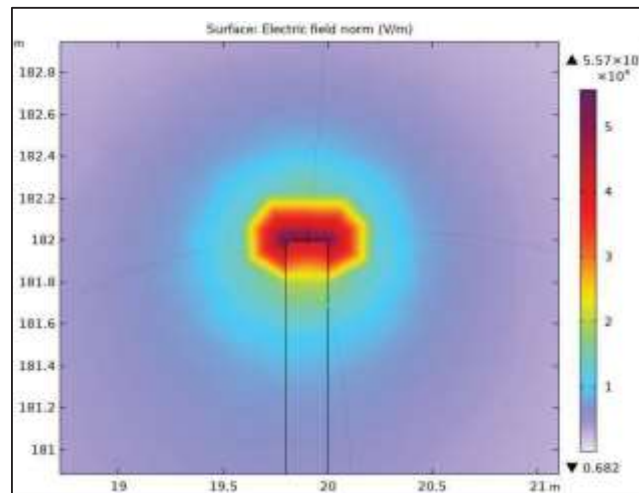


Figure 3. Electric field magnitude contours near the lightning rod tip

3.2 Increasing Height of Air Terminal

The air terminal and down conductor play a critical role in capturing and safely transferring lightning energy to the grounding system. The simulation results show a strong electric field concentration at the air terminal tip, while the conductor maintains a relatively uniform electric field distribution along its length. Figure 4 shows that increasing the air terminal height reduces the peak electric field intensity, indicating improved lightning interception performance.

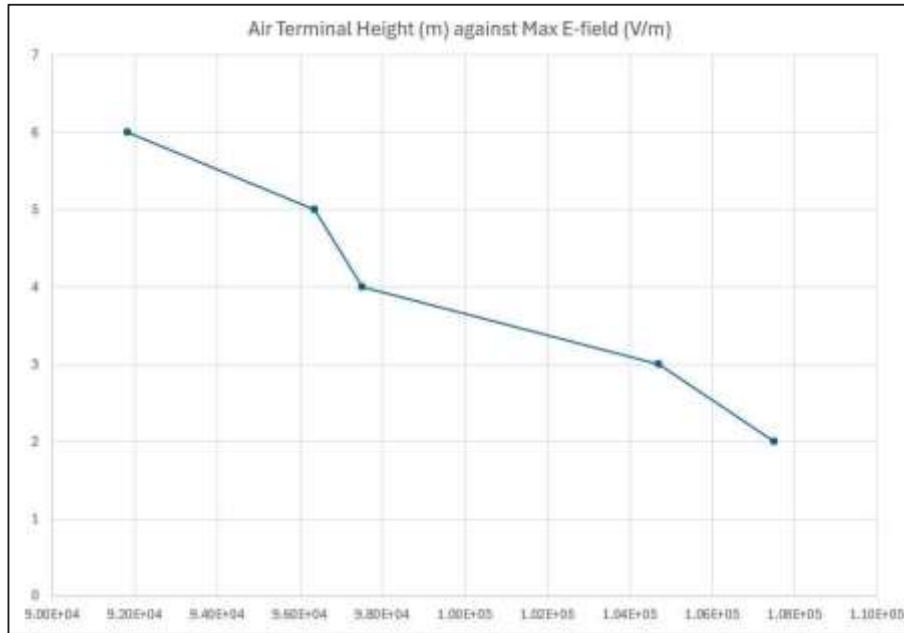


Figure 4. Increasing air terminal and its maximum E-field

3.3 Grounding System Performance Comparison

A comparative analysis of grounding configurations shows distinct differences in electric field dissipation. The ground rod configuration exhibits higher peak electric field values concentrated near the electrode, indicating localized field stress. The ground plate provides improved field dispersion due to increased contact area with the soil. The ground grid configuration demonstrates the most uniform electric field distribution with the lowest peak field magnitude, attributed to its extensive surface area and multiple current dispersion paths. Table 2 summarizes the maximum electric field intensity for different grounding configurations.

Table 2. Maximum E-Field for different grounding configurations

Grounding Method	Maximum Electric Field (V/m)
Vertical Rod	6.71e4
Horizontal Plate	6.6e4
Ground Grid	6.472e4

3.4 Final Proposed LPS Configuration

The proposed LPS integrates simulation-based performance evaluation with established design standards, resulting in balanced and practically feasible LPS configuration for high-rise buildings. Table 2 shows based on the combined outcomes of the air terminal height analysis and grounding performance evaluation, the final optimized LPS configuration is proposed as follows

Table 3. Final Optimized LPS configuration

LPS Component	Selected Configuration	Justification
Air Terminal	Standard-compliant height (IEC 62305/NFPA 780)	Practical installation with acceptable electric field performance
Down Conductor	Multiple down conductors along building perimeter	Improved current distribution and reduced localized concentration
Grounding System	Grid	Lowest maximum electric field intensity and effective charge dissipation

4. CONCLUSION

This paper presented a finite element-based evaluation of lightning protection system performance for high-rise buildings using electric field distribution as the primary assessment criterion. The behavior of air terminals, down conductors, and grounding systems under high-voltage excitation was examined using a two-dimensional electrostatic model. The findings show that the grounding setup has a major impact on electric field dissipation, with the ground grid configuration performing better due to a more uniform field distribution and lower peak electric field values. Finite element simulation is a useful technique for early stage LPS performance evaluation and design optimization, according to the study. The use of two-dimensional model and the neglect of transient lightning waveform impacts are two of the current work's limitations. To further improve the precision of LPS performance evaluation, future studies should include experimental validation and three-dimensional (3D) transient simulations.

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