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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 are time-consuming, limited in scope, and sometimes hazardous. In addition, most existing computational studies simplify building geometry or neglect local environmental factors, resulting in inaccurate evaluation of LPS performance in real urban conditions. To address this gap, this study develops a detailed COMSOL-based simulation model to evaluate the behavior of LPS in high-rise structures under realistic conditions. 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 results demonstrate that the LPS effectively maintains electric field levels below the air breakdown threshold, ensuring safe dissipation of lightning energy to the ground. The study provides deeper insight into LPS performance in complex urban environments, supporting the development of more reliable and predictive protection strategies for high-rise structures.

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).

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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.

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 studies have utilized FEM in lightning research, including work by Dąda 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.

Despite extensive studies, limited research focuses on LPS performance in the Malaysian context, particularly for high-rise buildings located in dense urban environments. The purpose of this study is to model and analyze electric-field distribution and potential behavior in an LPS equipped high-rise structure. While previous studies have modeled lightning behavior using simplified or generic building structures, this research introduces a more realistic urban high-rise configuration with detailed LPS components, including air terminals, down conductors, and soil grounding. The novelty of this study lies in integrating these physical parameters within a COMSOL Multiphysics environment to evaluate electric field and potential distribution specific to urban high-rise conditions in Malaysia. This approach provides improved accuracy and practical relevance for lightning protection design in dense metropolitan areas.

2. Methodology

2.1 Simulation Approach

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.

2.2 Geometry and Material Properties

The structure was represented by a rectangular concrete block, topped with a copper lightning rod connected to two vertical down conductors positioned at both sides of the building. A soil domain was placed beneath the building to represent the grounding system. The electrical parameters for each domain are listed in Table 1, based on values recommended by IEC 62305-3 [8] and NFPA 780 [9].

Table 1
Material Properties used in the simulation

Component	Relative Permittivity (ε_r)	Conductivity (S/m)
Air	1	-
Concrete	5	0.01
Copper	-	5.96×10^7
Soil	10	2

2.3 Boundary Conditions

An electric potential of 100 kV was applied to the tip of the lightning rod to represent a downward leader approaching the structure, as demonstrated by Guo et al. [9]. The bottom boundary of the soil was grounded at 0 V, while all other exterior boundaries were electrically insulated to prevent charge leakage.

2.4 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. Similar meshing strategies were used by Rizk [10] to study lightning exposure of tall structures. The stationary solver computed both the electric potential (V) and electric field (E) using standard FEM-based numerical techniques.

2.5 Model Assumptions and Schematic

The model assumes a steady-state (electrostatic) condition with a single downward lightning leader approaching the structure. Transient effects, multiple strikes, and side flashes are not considered in this analysis. The concrete building is assumed to have uniform material properties, and the surrounding air domain is treated as homogeneous.

A 2D schematic representation of the simulation domain, including the air region, building structure, lightning rod, down conductors, and soil grounding system, is shown in Figure 1. This figure provides a clear overview of the geometric layout used in COMSOL.

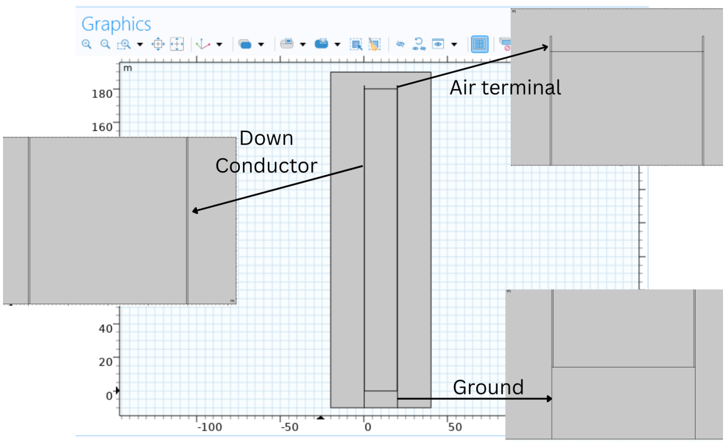

Fig. 1. Schematic representation of the simulation domain showing the building structure, lightning rod, down conductors, and soil grounding system in the COMSOL Multiphysics model.

The boundary conditions defining the potential, grounding, and insulation parameters in the COMSOL Multiphysics model are summarized in Table 2.

Table 2
Summary of boundary conditions used in the COMSOL simulation for the high-rise lightning protection model.

Boundary/Domain	Condition Type	Value/Description
Lightning rod tip	Electric potential	+100 kV
Ground (bottom soil)	Electric potential	0 V
Building surface	Continuity	-
Air boundariesl	Electrical Insulation	No charge leakage

3. Results

3.1 Electric Potential Distribution

The simulation results in Figure 2 show that the highest electric potential occurred at the lightning rod tip (100 kV), with a smooth decrease along the down conductors toward the ground. This gradient confirms that the LPS successfully directs the lightning energy away from the building surface. Comparable potential profiles were also reported by Negara et al. [4] in similar studies of high-rise protection systems.

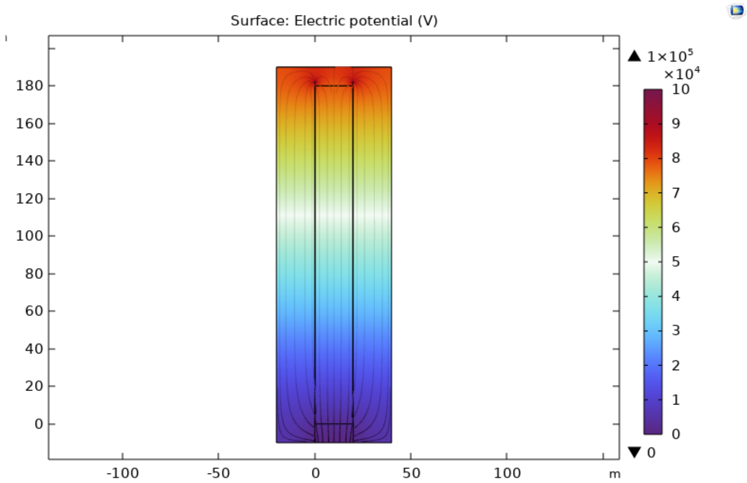

Fig. 2. Electric potential distribution along the high-rise building cross-section

3.2 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 Dąda 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 1.2×10^5 V/m, well within safe operating limits.

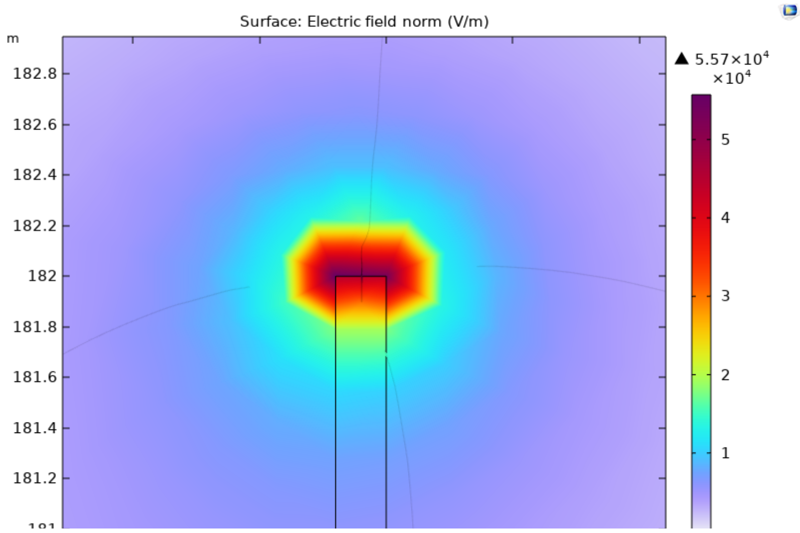

Fig. 3. Electric-field magnitude contours near the lightning rod tip

3.3 Electric Field Direction

Figure 4 demonstrates that the field lines follow a downward path along the copper conductors, terminating at the grounded region. A similar pattern was observed in studies by Rahman et al. [6] and Snider et al. [12], where proper conductor alignment ensured safe dissipation of charge into the ground. This verifies that the designed LPS effectively channels lightning current without intersecting occupied areas of the building.

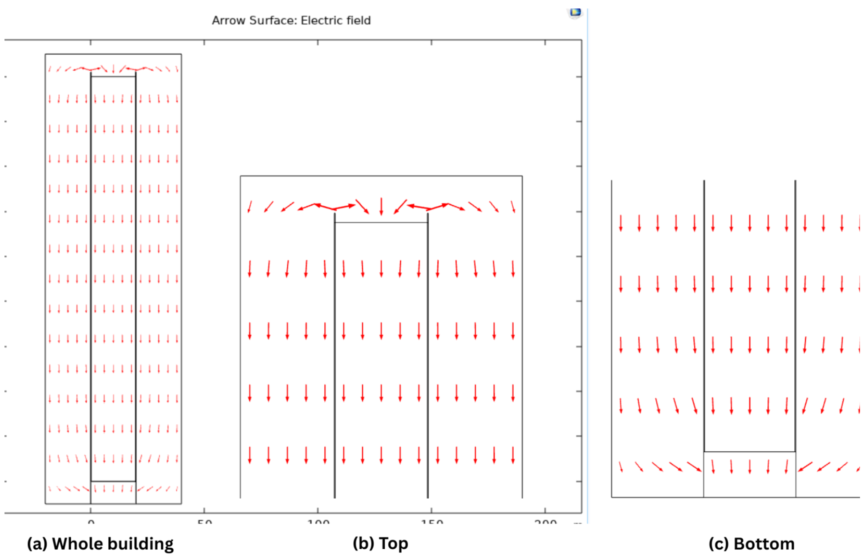

Fig. 4. Electric-field direction vectors surrounding the structure

3.4 Performance Implications

The simulation confirms that the proposed LPS design ensures uniform potential distribution, controlled electric-field concentration, and minimal risk of dielectric breakdown. The maximum field intensity of 1.82×10^6 V/m remains below the standard air breakdown threshold of 3×10^6 V/m, as specified by IEC 62305 and NFPA 780. This indicates that the LPS safely withstands direct lightning strikes without causing dielectric failure in the surrounding air.

The results also demonstrate that electric-field intensity along the building façade (approximately 1.2×10^5 V/m) is within safe operating limits, confirming effective shielding of occupied areas. Compared to previous work by Dąda et al. [4] and Rahman et al. [6], which focused on idealized structures, this study provides a more realistic representation of urban high-rise environments.

Furthermore, the analysis highlights that soil conductivity and grounding geometry significantly influence current dissipation efficiency. This finding agrees with Hardi et al. [14], who showed that higher soil conductivity enhances grounding performance. Thus, optimizing grounding design remains critical to improving overall LPS safety.

These observations collectively validate the simulation approach and demonstrate that COMSOL Multiphysics offers a reliable predictive tool for assessing lightning protection performance in complex urban settings.

4. Conclusions

This study presented a finite-element simulation of lightning-protection performance for an urban high-rise building. The 2D electrostatic model verified that:

1. The highest field concentration occurs at the lightning-rod tip
2. Potential is effectively conducted to ground through down conductors
3. The maximum field intensity (1.82×10^6 V/m) stays below the air-breakdown threshold (3×10^6 V/m).

These results confirm that the designed LPS provides adequate protection against direct strikes under simulated conditions. FEM-based modelling thus offers a reliable and cost-effective approach for preliminary evaluation of LPS in urban environments.

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