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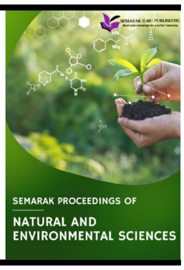

Analysis of Electric Field on Overhead Distribution Line due to Lightning Strike

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ABSTRACT

The increasing frequency of lightning phenomena, potentially due to climate change, poses significant threats to electrical systems and human safety when they are affected by lightning strikes, known as lightning-induced voltage (LIV). The LIV has a correlated procedure with lightning electromagnetic field (LEMF) and lightning channel base current. Therefore, a proper study needs to be conducted to analyze LEMF, particularly in vertical electric field behavior on the overhead distribution lines when lightning strikes tall structures. The study refers to IEEE 1410-2010 as a guideline and utilizes MATLAB software to generate the results of the lightning current and LEMF. It employs the Heidler model to simulate lightning current in Sabah and hybrid methods of the dipole and finite difference time domain for vertical electric field calculations. The results of the study reveal that the vertical electric field at clay soil resistivity is increased by 10% and reduced as the radial distance increases from the lightning strike point. These findings underscore the elevated risk of LEMF which later LIV in Sabah, necessitating additional precautionary measures. Furthermore, the study promotes the Sustainable Development Goals (SDG) 3, emphasizing healthy living and consumer well-being by ensuring zero fatalities within the electrical system. The study contributes to mitigating the increased lightning hazards in Sabah, an imperative step toward sustainable development and public safety.

Keywords: *Lightning; electromagnetic field; distribution power line; transmission line; tower*

1. Introduction

Lightning-induced voltage presents a significant risk to the reliability of Malaysia's power systems, particularly in Sabah, where the infrastructure predominantly utilizes overhead bare conductors [1-3]. This vulnerability arises from the coupling between lightning electromagnetic fields (LEMF) and power lines, which can induce transient overvoltage conditions. When lightning strikes, it generates electromagnetic fields that affect nearby electrical infrastructure through coupling mechanisms, especially with uninsulated overhead lines [3].

In Sabah, the reliance on overhead bare conductors exacerbates the impact of lightning events, as these conductors lack insulation, making them more susceptible to insulation breakdown and flashovers [4,5]. This heightened susceptibility can lead to significant operational disruptions, including visible sparks, electromagnetic interference, and potential damage to the power lines. As the region’s population continues to grow, so does the electricity demand, necessitating an

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expansion of the power infrastructure. With approximately 589 transmission towers in place, further development is crucial to ensure energy security and meet rising electricity needs while balancing affordability and environmental sustainability.

Given the potential for higher induced voltages due to the design of the distribution system, it is imperative to analyze the vertical electric field on these overhead lines in Sabah. The vertical electric field is a main component of LEMF that contributes to the LIV through the coupling mechanism. Understanding how lightning-induced voltages interact with the existing infrastructure can help utility companies develop strategies to enhance system reliability and protect against transient over voltages. By addressing these challenges, Sabah can ensure that its power system continues to support economic growth and improve the quality of life for its residents, even amid the uncertainties posed by lightning events.

2. Methodology

The methodology of this study is based on the Lightning Induced Voltage (LIV) procedure [6]. It comprises four main components: 1) channel base current, 2) lightning return stroke current, 3) lightning electromagnetic fields (LEMF), and 4) LIV. Each component is presented through mathematical equations, which are implemented using MATLAB software, as illustrated in Figure 1.

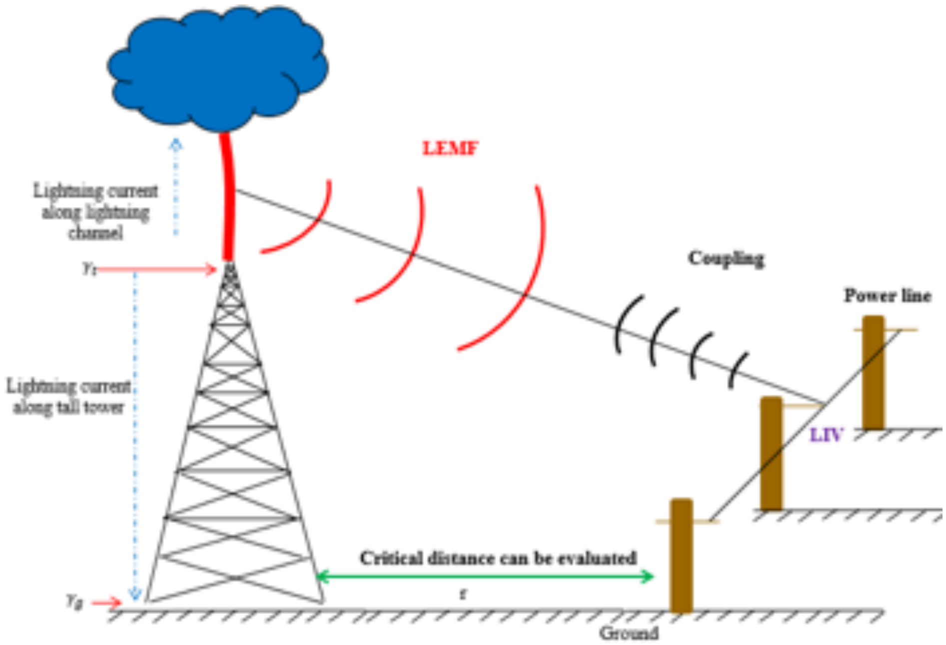


Fig. 1. An illustration of lightning-induced voltage for lightning striking a tall structure

2.1 Channel Base Current (CBC) Function

The lightning channel base current represents the initial lightning current that strikes either the ground or a tall structure. It can be expressed as mathematical function equations, which serve as inputs to the models of lightning return stroke and LEMFs. The channel base current function can be modeled using several approaches, including the Bruce-Golde (BG), Heidler, Diendorfer and Uman (DU), and Nucci models. In this study, the Heidler channel base current function, as shown in (1) and (2), is employed due to its similarity to the measured wave shape [6].

$$i(0,t) = \frac{I_0}{\eta}\frac{(t/\Gamma_1)^n}{1+(t/\Gamma_1)^n}\exp\left(\frac{-t}{\Gamma_2}\right) \tag{1}$$

$$\eta = exp - \left(\frac{\Gamma_1}{\Gamma_2}\right)^{\frac{1}{n}} \tag{2}$$

Where: i_0 is the amplitude of the channel base current, Γ_1 is the front time constant, Γ_2 is the decay-time constant, n is an exponent (2~10) and η is the amplitude correction factor.

2.2 Lightning Return Stroke Current

The lightning return stroke current represents the distribution of the lightning current when the current "bounces" back to the lightning channel due to impedance differences between the channel and the point of impact. In this study, the lightning strikes tall towers. At the beginning of the first strike at the top of the tower, the lightning current propagates downward along the tower while simultaneously moving upward along the channel [7].

The behavior of the lightning return stroke current can be modeled using several mathematical equations, such as the Bruce-Golde (BG) model, the Travelling Current Source (TCS) model, the Transmission Line (TL) model, the Modified Transmission Line with Exponential Decay (MTLE) model, and the Modified Transmission Line Linear (MTLL) model. In this study, the Modified Transmission Line with Exponential Decay model (MTLE) is used to represent a decreasing current with an exponential decay as channel height increases, as shown in Eq. (3) to Eq. (5).

$$i(t,z) = i\left(t - \frac{z}{v}\right) A(z) \quad t \geq \frac{z}{v} \tag{3}$$

$$i(t,z) = 0 \quad t < \frac{z}{v} \tag{4}$$

$$A(z) = \exp(-z/\lambda) \tag{5}$$

Where: z is a vertical space variable, v is the lightning wave-front velocity and H is the channel height.

2.3 Lightning Electromagnetic Field (LEMF)

The dipole method is used to evaluate the LEMF behavior as shown in Eq. (6) to Eq. (8).

$$dE_r = \frac{I_0 dz'}{4\pi\epsilon_0}\left[\begin{matrix}\frac{3r(z-z')}{R^5}\left(t - \frac{R}{c} - \frac{|z'|}{v}\right).u\left(t - \frac{R}{c} - \frac{|z'|}{v}\right) + \left[\frac{3r(z-z')}{cR^4}\right]. \\ u(\left(t - \frac{R}{c} - \frac{|z'|}{v}\right) + \left[\frac{r(z-z')}{c^2R^3}\right]\delta\left(t - \frac{R}{c} - \frac{|z'|}{v}\right)\end{matrix}\right] \tag{6}$$

$$dE_z = \frac{I_0 dz'}{4\pi\epsilon_0}\left[\begin{matrix}\frac{2r(z-z')^2 - r^2}{R^5}\left(t - \frac{R}{c} - \frac{|z'|}{v}\right). \\ u\left(t - \frac{R}{c} - \frac{|z'|}{v}\right) + \left[\frac{2r(z-z')^2 - r^2}{cR^4}\right]. \\ u\left(t - \frac{R}{c} - \frac{|z'|}{v}\right) + \left[\frac{r^2}{c^2R^3}\right]\delta\left(t - \frac{R}{c} - \frac{|z'|}{v}\right)\end{matrix}\right] \tag{7}$$

$$dH(r,z,t) = \frac{I_0 dz'}{4\pi\epsilon_0}\begin{bmatrix} \frac{r}{cR^2}\delta\left(t-\frac{R}{c}-\frac{|z'|}{v}\right) \\ +\frac{r}{R^3}u(\left(t-\frac{R}{c}-\frac{|z'|}{v}\right) \end{bmatrix} \tag{8}$$

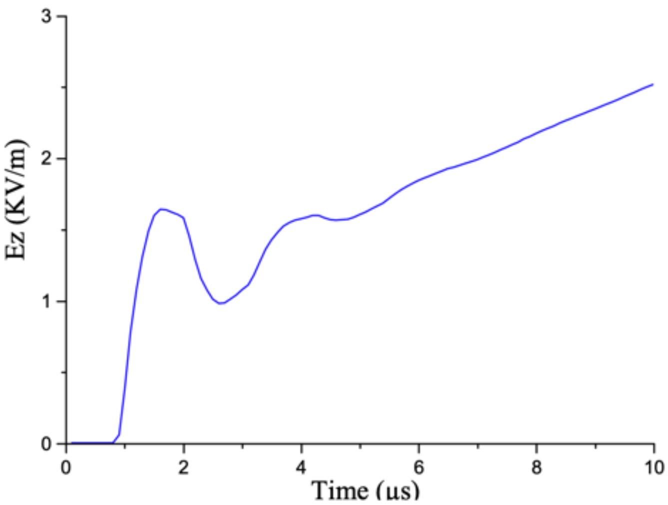
where: β is a $\frac{v}{c}$, r is a radial distance, c is the speed of light and v is a return stroke velocity

In this study, the vertical electric field is evaluated using the Finite Difference Time Domain (FDTD) method as shown in Eq. (9).

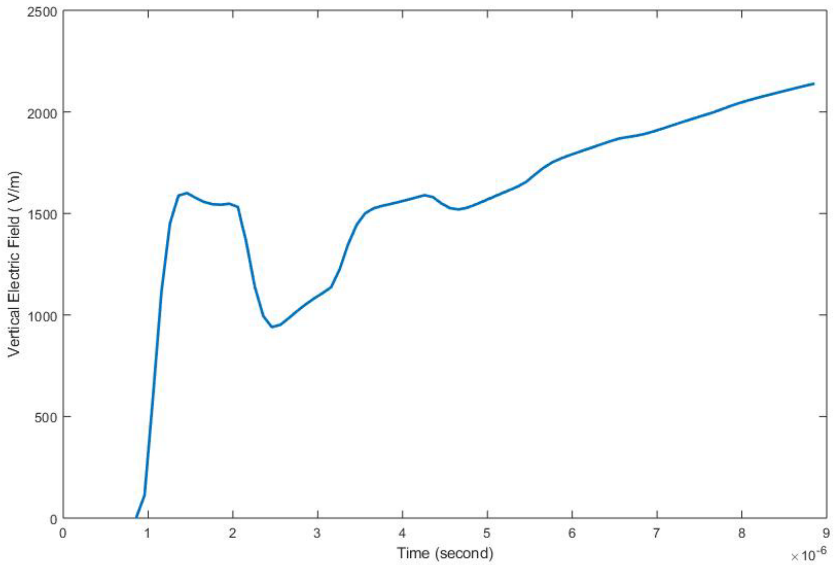
$$E_z = \Delta t * dE_z(i,1) + E_z(i-1,1) \tag{9}$$

where Δt is the time step while i is the iterative step.

Furthermore, the vertical electric field is validated against the measured values found in Brignone *et al.,* [8] and Baba *et al.,* [9] as shown in Figure 2. It is important to note that the vertical electric field is a key component in calculating the LIV.



(a)



(b)

Fig. 2. Vertical electric field validation (a) The vertical electric field measured at 195m from Peissenberg tower [9] (b) The vertical electric field simulated at 195m from Peissenberg tower

The validation results show a close match between the simulated and measured values, with the percentage difference during the first 3 microseconds falling within an acceptable margin of less than 10%.

2.4 Ground Reflection Factor (GRF)

The ground reflection factors, y_g are correlated between the two impedances shown in Eq. (10). These factors represent the reflected lightning current when there are differences between ground impedance and tower impedance causing the current to travel down the tower again, repeating the process until all the energy is absorbed. Therefore, the ground impedance z_g plays a significant impact since dependable on the soil resistivity and grounding arrangement shown in Eq. (11) and detailed in Table 1.

$$y_g = \frac{Z_t - Z_g}{Z_t + Z_g} \quad (10)$$

$$z_g = \frac{\rho}{2\pi L v}\left[\left(\ln \frac{4Lv}{a}\right) - 1\right] \quad (11)$$

Where: z_t and z_g are present the impedance tower, and ground impedances respectively, ρ is the soil resistivity, L_V is the length of the vertical conductor, and a is the radius of the conductor.

Table 1
GRF value based on soil types [10]

Soil Type	Max value of soil resistivity (Ωm)	Ground Impedance, Z_g (Ω)	Ground Reflection Factor, y_g
Sand	900	82.50	0.57
Clay	100	9.17	0.94
Silt	97	8.89	0.94
Gravel	800	73.33	0.61
Alluvium	850	77.92	0.59
Peat	500	45.83	0.74
Silty Clay	45	4.13	0.97

3. Results

The analysis of vertical electric field distribution on the overhead line due to lightning striking a tall structure was conducted by considering parameters such as peak current, reflection factors for different soil resistivities, and the radial distance from the lightning strike to the distribution line.

3.1 Channel Base Current at Sabah

The graph in Figure 3 shows the peak lightning current in Sabah [4], with the highest recorded peak at approximately 54.59 kA, indicating that lightning strikes in Sabah are particularly intense. This has significant implications for the design and protection of electrical infrastructure in the region.

The severity of a lightning strike and the possibility of power system damage increase with increasing channel base current. The higher the channel base current, the higher the LEMF, which leads to a higher LIV. As a result, power systems may experience severe disruptions which can result in malfunctions, damage to equipment, and even total system failures.

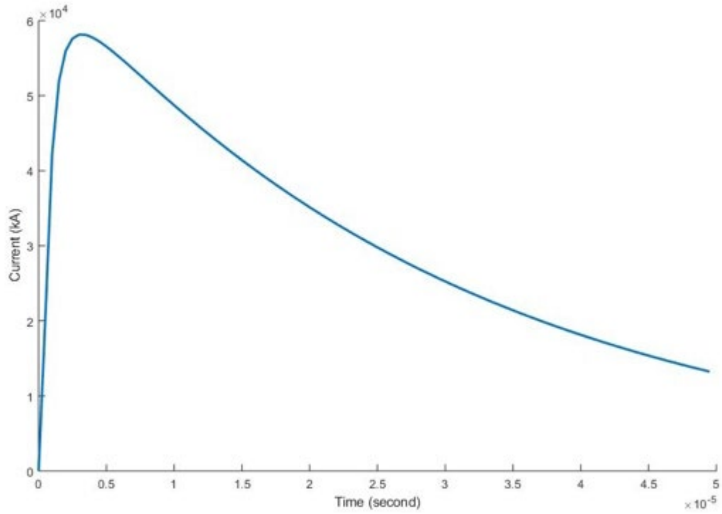


Fig. 3. Channel base current function in Sabah

3.2 Analysis of Vertical Electric Field with Various Types of Soil and Radial Distance on The Peak Current at Sabah

Figure 4 provides valuable insights into the peak values of the vertical electric field induced by a current peak of 54.59 kA at various radial distances and across different soil types. As expected, the strength of the vertical electric field decreases with distance from the source. This information is crucial for understanding the behavior of LEMFs and their potential impact on different environments.

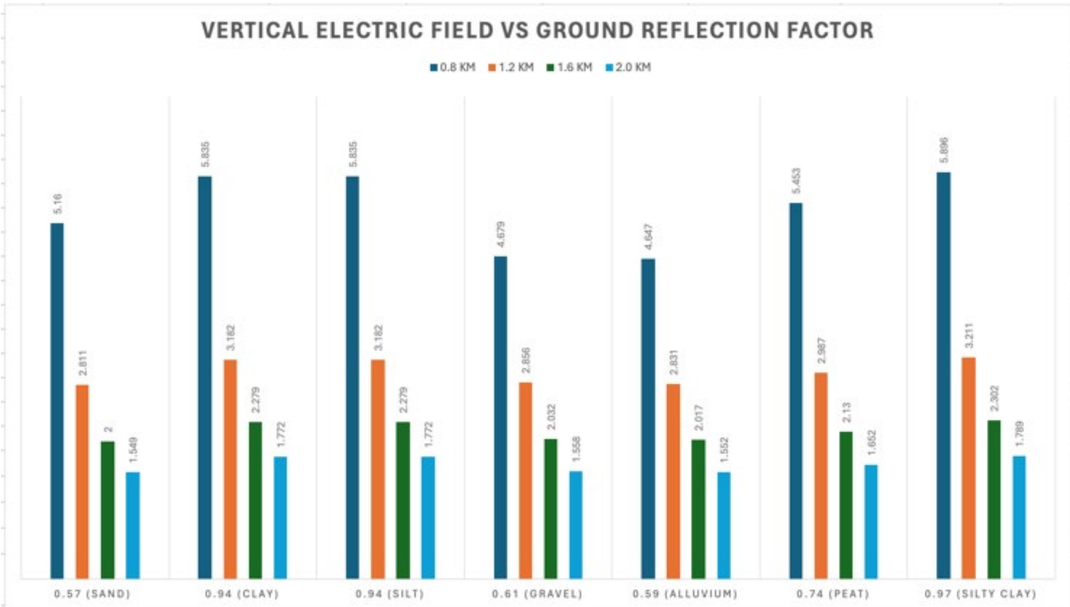


Fig. 4. Full plotting of vertical electric field peak value various radial distances with different types of soil

The results indicate that soils with higher Ground Reflection Factors (GRF), such as Silty Clay (0.97), exhibit higher initial electric field values. For instance, Silty Clay shows a vertical electric field of 5.896 kV/m at 0.8 km, which decreases to 1.789 kV/m at 2.0 km. In contrast, soils with lower GRF, like Sand (0.57), demonstrate lower electric field values, starting at 5.160 kV/m and dropping to 1.549 kV/m over the same distances.

Additionally, the vertical electric field across different soil types at 0.8 km ranges from 4.647 kV/m to 5.896 kV/m. As the distance increases to 2.0 km, these values reduce to between 1.549 kV/m and 1.789 kV/m. This significant reduction illustrates how the intensity of the vertical electric field diminishes as the distance from the lightning strike point increases, following the inverse-square law, which states that the field strength is inversely proportional to the square of the distance from the source.

4. Conclusions

This study thoroughly analyzes the behavior of vertical electric fields on overhead distribution lines in Sabah when lightning strikes tall structures. The primary findings reveal that soil resistivity and radial distance significantly affect the propagation of the vertical electric field. Soils with higher GRF exhibit higher initial electric field values, while soils with lower GRF demonstrate lower electric field values. Furthermore, the vertical electric field induced by lightning shows a rapid decrease in intensity as the distance from the strike point increases. The consistent decline in the vertical electric field with increasing radial distance across all soil types highlights the importance of distance in mitigating the effects of lightning-induced electric fields. Additionally, the significant differences in electric field values among various soil types underscore the necessity for tailored approaches in managing the impacts of LEMFs in diverse environments.

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