Jurnal Kejuruteraan 38(3) 2026: 1473-1481
https://doi.org/10.17576/jkukm-2026-38(3)-37

Lightning Electromagnetic Field Behavior on the Overhead Distribution Line in Sabah

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Received 31 July 2025, Received in revised form 13 November 2025
Accepted 18 December 2025, Available online 30 May 2026

ABSTRACT

The increasing frequency of lightning phenomena, potentially intensified by climate change, presents serious risks to electrical infrastructure and public safety, mainly through lightning-induced voltage (LIV) affecting overhead distribution lines. This study examines the Lightning Electromagnetic Field (LEMF) behavior in Sabah using IEEE 1410-2010 guidelines and MATLAB simulations. Mathematical models representing lightning discharge processes were developed and implemented using the Heidler current model for the channel base current and the Modified Transmission Line with Exponential Decay (MTLE) model for the return stroke. The dipole method and the Finite Difference Time Domain (FDTD) technique were employed to evaluate spatial and temporal field distributions. Model validation shows strong agreement between measured and simulated waveforms, with percentage differences below 10%. Waveform parameters such as amplitude and rise time closely match empirical data, confirming the model accuracy. Analysis incorporating Sabah-specific lightning current data indicates that current magnitudes are about 10% higher than in Peninsular Malaysia, resulting in 5–10% increase in LEMF peak values, influenced by soil resistivity. The LEMF response contributes directly to LIV through electromagnetic coupling, increasing stress on electrical networks. These findings emphasize Sabah's heightened vulnerability to lightning-induced overvoltages and the need for improved protection and grounding systems. The study advances understanding of regional lightning behavior and supports Sustainable Development Goal (SDG) 3 by promoting safer and more resilient power infrastructure.

Keywords: Lightning; electromagnetic field; induced voltage

INTRODUCTION

Lightning-induced voltage presents a significant risk to the reliability of Malaysia's power systems, particularly in Sabah, where the infrastructure predominantly consists of overhead bare conductors (Chambers et al. 2023; The News of Communications Ministry 2024; Jaafar et al. 2023). This vulnerability stems from the coupling between lightning electromagnetic field (LEMF) and power lines, which can induce transient lightning overvoltage conditions. When lightning strikes, it generates electromagnetic fields that can affect nearby electrical infrastructure, especially uninsulated overhead lines (IEEE Std 1410-2010; Jaafar et al. 2023; Yating et al. 2022). The phenomenon can be categorized into direct and indirect effects: direct strikes typically result in higher voltage levels when they hit power line components directly, while indirect strikes can induce voltage when lightning strikes the ground or objects nearby, leading to electromagnetic coupling.

Research has shown that the LEMF can be influenced by the first or subsequent lightning current (Cooray et al. 2023; Liu et al. 2020) which examined the LEMF using mathematical modelling and experimental work, respectively. They found that the LEMF consists of vertical, horizontal and magnetic field components, these components all of which contribute to LIV. Also, few studies have been conducted on the LEMF response in overhead distribution systems. The literature indicates that the LEMF is affected by lightning channel base current and parameter values, most of which are assumed to be typical values. Therefore, this study further investigates the behavior of LEMF on overhead distribution lines with respect to local parameters, with particular focus on Sabah, Malaysia. Also, the mathematical formulation for calculating LEMF is introduced. It shall be noted that the LEMF significantly contributes to the generation of LIV. The higher the LEMF response, the greater induced voltage will be generated in the system. The reliance on overhead bare conductors increases the impact of lightning events, as these conductors lack insulation, making them more prone to insulation breakdown and flashovers (Izadi et al. 2014; Agrawal et al. 2014). This heightened susceptibility can lead to significant operational disruptions, including visible sparks, electromagnetic interference, and potential damage to the power lines.

In Sabah, the region's population continues to grow, the demand for electricity increases accordingly, necessitating an 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 (Chambers et al. 2023). Given the potential for higher induced voltages due to the design of the distribution system, it becomes imperative to investigate the effects of LEMF on these overhead lines in Sabah (Mohamad et al. 2022) which there is still a significant lack of research and information in Sabah. Understanding how LEMF interacts with the existing infrastructure can help utility companies develop strategies to enhance system reliability and protect against transient overvoltages.

Thus, the aim of this study is to determine the effects of lightning electromagnetic field behavior on the overhead distribution line in Sabah by considering variation of soil resistivity and critical safety distance towards line. 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. Also, with the promise of supplying dependable and robust electricity, this study has the potential to significantly benefit the community and utility provider to provide the Sabah community with reliable and efficient power solutions.

METHODOLOGY

The study framework outlines the various steps involved in achieving the objectives of this study. Accordingly, a framework was developed based on the LIV procedure described in IEEE Std 1410-2010. It comprises the evaluation of channel base current, lightning return stroke current along the channel and the tower, and LEMF as shown in Figure 1. It shows the position of lightning current, and the generated LEMF, and the critical distance evaluated in this study.

When a tall structure or tower is struck by lightning, an event initiates a phenomenon characterized by the lightning channel base current, which triggers electromagnetic processes. These processes result in the coupling between the lightning channel and nearby conductors, leading to induced voltage within the system. In the context of mathematical modelling, LEMF response at a specific observation point, typically located a few meters away from the base of a lightning-struck tower can be determined by analysing the distribution of the lightning current along both the lightning channel and the tower itself. This process involves a detailed computation of how the current behaves and reflects along the structure.

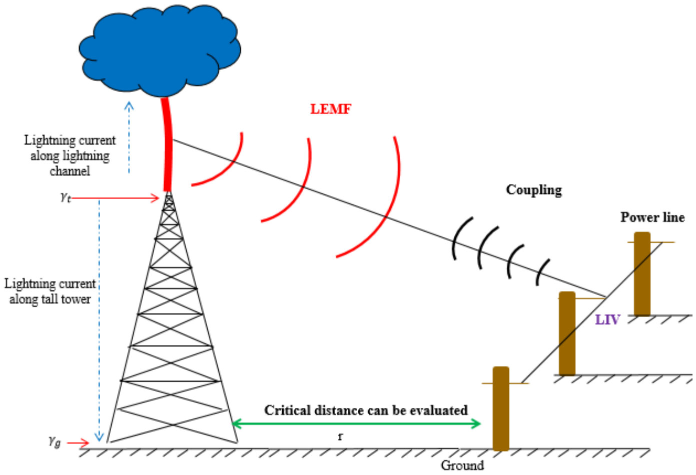


FIGURE 1. Lightning strike on a tall tower (Rameli N. 2017)

The overall procedure used to evaluate these responses is illustrated in the flowchart shown in Figure 2. As depicted, the modelling process begins with defining the configuration parameters of the lightning current, such as peak amplitude, rise time, and propagation characteristics. These parameters are essential, as they form the foundation for simulating the lightning return stroke current, which is subsequently implemented within the computational model.

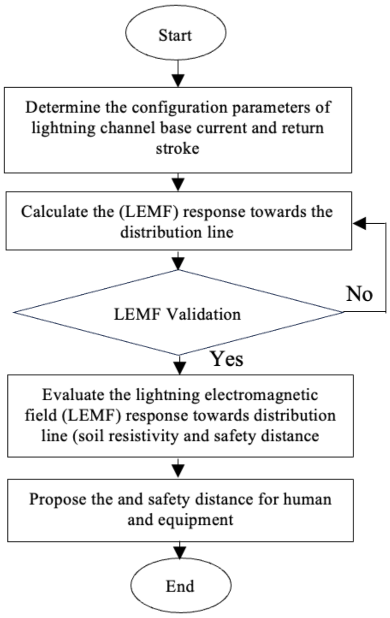


FIGURE 2. The procedure of flowchart for evaluating the LEMF behavior

To ensure the accuracy and reliability of the results obtained through this modelling process, a validation stage was conducted, comparing the simulated LEMF responses with existing experimental data. The entire simulation and analysis workflow were carried out using the MATLAB software, which provided a robust platform for numerical calculations and graphical representations throughout the study.

LIGHTNING CURRENT

Lightning current consists of channel base current and lightning return stroke current. Lightning channel base presents the first strike of lightning that hits at the top of tower. On the other hand, lightning return strokes present the propagation of lightning current at speed of light upward through the lightning channel and downward through the tower. Both of these lightning currents are required and important in calculating the LEMF. Different mathematical equations were expressed to present the channel base current (Kutsuna et al 2022; Izadi et al. 2017). In this study, the Heidler current function expressed in Equation (1) and (2) is chosen.

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

Where: Where: i_0 is the amplitude of the channel base current, Γ_1 is the front time constant, and Γ_2 is the decay-time constant.

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

Where: n is an exponent (2~10), and n is the amplitude correction factor.

Moreover, the lightning return stroke current represents the propagation of lightning current towards the lightning channel and the tall tower whereby the lightning current will start to propagate downward along the tower at the speed of light and at the same time upward along the channel at the return stroke velocity. The propagation of lightning current can be represented by mathematical models established by (Rachidi et al 2002) shown in Equation (3) and (4). Note that, several mathematical models have also been established Silveira et al. (Silveira et al. 2014; Behzad et al 2003).

$$i(z',t) = \left[P(z'-h_t)i_o\left(h_t, t-\frac{z'-h_t}{v}\right)-\gamma_t i_o\left(h_t, t-\frac{z'-h_t}{c}\right) + (1-\gamma_t)(1+\gamma_t)\sum_{n=0}^{\infty} \gamma_g^{n+1}\gamma_t^n i_o\left(h, t-\frac{z'+h_t}{c}-\frac{2nh_t}{c}\right)\right] \tag{3}$$

The current distribution along the lightning channel with $h_t < z' < H$

Where: γ_t and γ_g are the top and ground current reflection coefficients respectively, n is the number of reflection currents inside the tower, h_t is the height of the tower, i_o is a current function, c is the speed of light for the waves that propagate in the tower, v is the speed of the upward lightning channel for the waves that propagate in the lightning channel, $P(z'-h_t)$ is a model-dependent attenuation function, and $u(t)$ is the Heaviside unit-step function.

$$i(z',t) = (1\text{-}\gamma_t)\sum_{n=0}^{\infty}\left[\gamma_t^n\gamma_g^n i_o\left(h_t, t\text{-}\frac{h_t\text{-}z'}{c}\text{-}\frac{2nh_t}{c}\right) + \gamma_t^n\gamma_g^{n+1} i_o\left(h_t, t\text{-}\frac{h_t+z'}{c}\text{-}\frac{2nh_t}{c}\right)\right] \quad (4)$$

The current distribution along the tower with $0 \le z' \le h_t$

Where:γ_t and γ_g are the top and ground current reflection coefficients respectively, n is the number of reflection currents inside the tower, h_t is the height of the tower, i_o is a current function, c is the speed of light for the waves that propagate in the tower, v is the speed of the upward lightning channel for the waves that propagate in the lightning channel, and $u(t)$ is the Heaviside unit-step function.

In addition, the expression of P $(z'\text{-}h_t)$ in Equation 3 is based on the return stroke current model which presents the behavior of lightning return stroke current along the channel. Different mathematical expressions were expressed (Vernon et al. 2024; Adepitan and Oladiran 2012; Ramarao and Chandrasekaran 2019; and Dib et al 2007). In this study, the Modified Transmission Line with Exponential Decay (MTLE) model is used, as expressed in Equations (5) to (7). The MTLE provides a more realistic representation of lightning current propagation by incorporating exponential decay with height, which closely matches observed lightning behavior. This enhances the accuracy of the computed electromagnetic fields, especially in near-field conditions.

$$i(t,z) = i(t - \tfrac{z}{v})\, A(z) \quad t \ge \frac{z}{v} \quad (5)$$

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

$$i(t,z) = 0 \qquad\qquad t < \frac{z}{v} \quad (6)$$

$$A(z) = exp\,(-z/\lambda) \quad (7)$$

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

Lastly, the propagation of lightning current is strongly affected by the reflection factor. It is due to the impedance difference between the ground and the tower, as well as between the tower and the channel. A reflection event known as the travelling wave phenomenon will continue to occur until the energy of the lightning current has dissipated. The phenomenon expressed by γ_t and γ_g is further explained in the next section.

REFLECTION FACTOR

Reflection factors consist of Ground reflection factor (GRF), γ_g and top reflection factor,γ_t. In this study, the top reflection factors are kept constant while the GRF varies based on the local soil resistivity as tabulated in Table 1 (Zamri S.N et al 2023; Jeffery et al 2022). The equations for GRF are given in Equation (8) and (9).

$$z_g = \frac{\rho}{2\pi Lv}\left[\left(ln\, ln\, \frac{4Lv}{a}\right) - 1\right] \quad (8)$$

Where: z_g is presents the impedance ground impedances, ρ is the soil resistivity, L_v is the length of the vertical conductor, and a is the radius of the conductor.

$$\gamma_g = \frac{Z_g - Z_{ch}}{Z_g + Z_{ch}} \quad (9)$$

Where:z_{ch} It presents the impedance channel.

TABLE 1. The GRF for the maximum typical value of soil resistivity in Sabah (Zamri S.N et al 2023; Jeffery et al 2022)

Soil Type	Max value of soil resistivity (Ωm)	Ground Impedance, z_g (Ω)	Ground Reflection Factor, γ_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

CALCULATION OF LIGHTNING ELECTROMAGNETIC FIELD (LEMF) RESPONSE

LEMF comprises the components of electric and magnetic fields that become vital in the modelling of the LIV. The LEMF components are calculated at a perception point that is situated in a certain range on the level ground surface with a separation of a few meters from the tall struck tower (Rameli N. 2017) as shown in Figure 3.

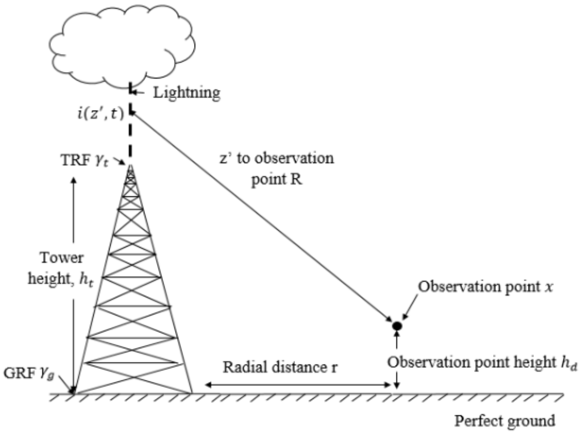


FIGURE 3. Calculation of LEMF geometry with respect to a lightning strike on a tall tower

Different mathematical equations were expressed to present the lightning electromagnetic field (LEMF) calculation (He-Ming et al 2008; Brignone et al. 2022; Alice et al 2023; Pan Duan et al. 2023). In this study, the dipole method and Finite Difference Time Domain (FDTD) are used to calculate the lightning electromagnetic field (LEMF) behavior on overhead distribution lines as shown in Equations (10) to (12).

$$dE_r = \frac{I_0 dz'}{4\pi\epsilon_0}\left[\frac{3r(z-z')}{R^5}\left(t-\frac{R}{c}-\frac{|z'|}{v}\right).u\left(t-\frac{R}{c}-\frac{|z'|}{v}\right)+\left[\frac{3r(z-z')}{cR^4}\right].\ u(\left(t-\frac{R}{c}-\frac{|z'|}{v}\right)+\left[\frac{r(z-z')}{c^2R^3}\right]\delta\left(t-\frac{R}{c}-\frac{|z'|}{v}\right)\right] \quad (10)$$

$$dE_z = \frac{I_0 dz'}{4\pi\epsilon_0}\left[\frac{2r(z-z')^2-r^2}{R^5}\left(t-\frac{R}{c}-\frac{|z'|}{v}\right).u\left(t-\frac{R}{c}-\frac{|z'|}{v}\right)+\left[\frac{2r(z-z')^2-r^2}{cR^4}\right].\ u\left(t-\frac{R}{c}-\frac{|z'|}{v}\right)+\left[\frac{r^2}{c^2R^3}\right]\delta\left(t-\frac{R}{c}-\frac{|z'|}{v}\right)\right] \quad (11)$$

$$dH(r,z,t) = \frac{I_0 dz'}{4\pi\epsilon_0}\left[\frac{r}{cR^2}\delta\left(t-\frac{R}{c}-\frac{|z'|}{v}\right)+\frac{r}{R^3}u(\left(t-\frac{R}{c}-\frac{|z'|}{v}\right)\right] \quad (12)$$

A further equation for the FDTD was expressed to calculate the vertical electric field shown in Equation (13).

$$E_z = \Delta t * dE_z(i,1) + E_z(i-1,1) \quad (13)$$

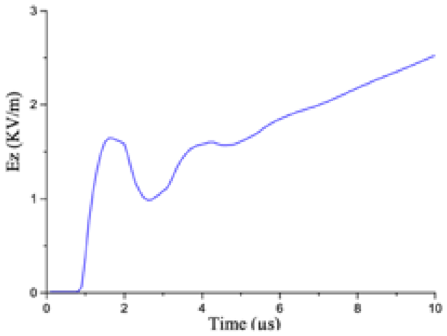
Where Δt is the time step while *i* is the iterative step.

VALIDATION OF LIGHTNING ELECTROMAGNETIC FIELD (LEMF)

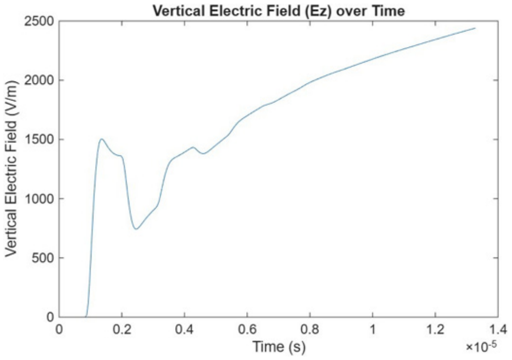
To confirm the reliability of the study, the calculation of the LEMF was validated against published paper (Mohamed & Abdeni et al. 2018; Guerrieri et al. 1998). The data, including the GRF values presented in Table 2, were obtained from these studies, which were based on experimental measurements conducted at Peissenberg Tower in Germany. Table 2 summarizes the experimental parameters, while Figure 4 illustrates the validation of the vertical electric field.

TABLE 2. Peissenberg Tower, Germany parameters to obtain lightning electromagnetic field (LEMF) (Mohamed & Abdeni et al. 2018; Guerrieri et al. 1998)

Parameters	Values
Tower Height	168 m
Radial distance	195 m
Ground Reflection Factors (GRF)	0.85
Top Reflection Factors	-0.5
Rolling sphere velocity, v	1.5x10^{8}m/s
Speed of light, c	3x10^{8}m/s



(a) Measured field



(b) Simulated field

FIGURE 4. Vertical electric field at 195 m from Peissenberg Tower, Germany (measured field from Mohamed & Abdeni et al. 2018; Guerrieri et al. 1998)

The figure demonstrates a close match between the measured and simulated field, with the percentage difference between the values less than 10% for the first of 5 µs shown in Table 3. Moreover, the simulated field waveform nearly matches the measured data's, confirming the model's and code accuracy. Overall, the simulation closely aligns with the measurements, with most differences being relatively low. Table 4 shows the simulated lightning channel base current parameters used for validation, considering a simulation time step of 5×10^{-8}s and a distance step of 250 m in the configuration.

TABLE 3. Percentage difference between the measured and simulated field

Time, µs	Vertical electric field, kV/m		Percentage difference, %
	Measured	Simulated	
1.45	1.47	1.60	8.46
2.00	1.36	1.32	2.98
3.00	1.03	1.00	2.95
4.00	1.40	1.46	4.19
5.00	1.35	1.45	7.14

TABLE 4. Simulated data value

Parameter	i_o(kA)	Γ_1(µs)	Γ_2(µs)	n
First Stroke, i_{first}	14	0.75	30	2

The study was further extended to examine the detailed effects of LEMF on soil resistivity and safety distance. It is well established that the interaction between the LEMF and soil resistivity significantly influences the magnitude and behaviour of lightning induced voltage on overhead distribution lines. In this analysis, the tower is assumed to be uniform, with the propagation speed along the structure equal to speed of light and the tower reflection coefficient is frequency independent.

RESULTS AND DISCUSSION

The LEMF results are presented by considering the effects of lightning peak current, radial distance, and soil resistivity. The safety distance of the LEMF with respect to the overhead bare conductor is also discussed. Figure 5 illustrates the trend of the vertical electric field generated by a lightning current peak of 54.59 kA (Meteologix Malaysia 2024) at various distances (0.8 km to 2.0 km) from the lightning strike point for different soil type.

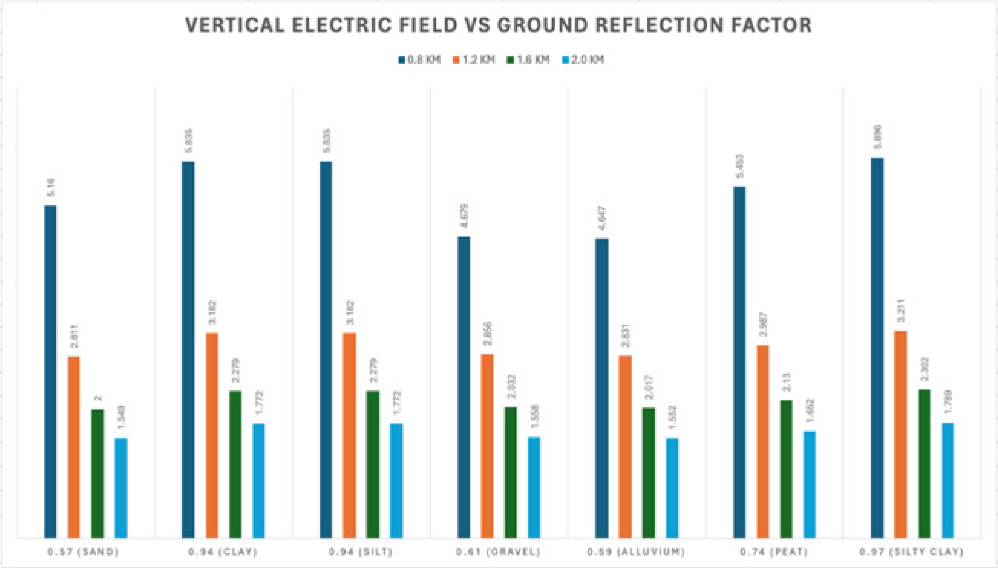


FIGURE 5. The vertical electric field trend at various distances with different soil types

Across all soil types, the vertical electric field decreases with increasing distance from the strike point. This trend aligns with the typical behavior of electromagnetic field propagation, where the field strength diminishes with radial distance due to energy dispersion and attenuation through the soil. Moreover, soil resistivity and GRF significantly influence the magnitude of electric field. Soils with higher GRF values (e.g., Silt and Silty Clay at 0.94 and 0.97, respectively) generally show higher vertical electric field values. For example, Silty Clay exhibits the highest average vertical electric field of 3.30 kV/m**,** followed by Silt and Clay (both at 3.27 kV/m)**,** indicating that higher resistivity soils tend to retain and transmit more electric field strength.

On the other hand, the Gravel (GRF = 0.61) and Alluvium (GRF = 0.59) show lower average vertical electric field values of 2.78 kV/m and 2.76 kV/m, respectively. These values are among the lowest, second only to Sand (2.88 kV/m). This suggests that soils with lower GRF (and possibly better conductivity) help to attenuate the electric field more effectively, potentially offering better electromagnetic compatibility characteristics as well as LIV values on the overhead bare conductor.

Hence, the relatively lower electric field values observed in Gravel and Alluvium support that these soil types may provide more favorable conditions for grounding system performance and improved mitigation of lightning electromagnetic field (LEMF). Table 5 shows the vertical electric field simulated value at the varies of soil resistivity.

TABLE 5. Vertical electric field peaks at various distances with different types of soil.

Type of Soil	GRF	Vertical electric field (kV/m)				
		Distance (km)				Average
		0.8	1.2	1.6	2.0	
Sand	0.57	5.16	2.81	2.00	1.55	2.88
Clay	0.94	5.83	3.18	2.28	1.77	3.27
Silt	0.94	5.83	3.18	2.28	1.77	3.27
Gravel	0.61	4.68	2.86	2.03	1.56	2.78
Alluvium	0.59	4.65	2.83	2.02	1.55	2.76
Peat	0.74	5.45	2.99	2.13	1.65	3.05
Silty Clay	0.97	5.90	3.21	2.30	1.79	3.30

Moreover, to assess the safety distances related to vertical electric field exposure that may affect residential areas and equipment, further analysis was conducted on the distance from the lightning strike point as well as the type of soil. According to The International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines, the recommended exposure limit for the public is 5 kV/m for electric fields, and 100 μA/m for magnetic fields. These limits are based on current scientific understanding and are designed to prevent any known adverse health effects resulting from short or long-term exposure to non-ionizing radiation.

Given these stringent safety thresholds considering that regions such as Sabah exhibit relatively higher levels of LEMF due to frequent and intense lightning activity, it becomes critical to assess and implement appropriate safety distances. These distances are necessary to ensure that the residential areas are not exposed to field strengths exceeding the recommended ICNIRP limits.

The vertical electric field under various soil conditions at 0.8 km from the lightning strike point have shown values ranging from approximately 4.647 kV/m to 5.896 kV/m. This indicates that even at that range, the electric field strength in some soil types already exceeds the ICNIRP limit of 5 kV/m. However, when the distance increases to 2.0 km, the electric field reduces significantly to values between 1.549 kV/m and 1.789 kV/m, which are safely within the acceptable range.

Based on these findings, to ensure that the electric field exposure remains below the 5 kV/m limit as referred to by the ICNIRP guidelines, a minimum safety distance of over 1.2 km is suggested to be maintained in most common soil types. However, for Silty Clay soil, which appears to retain higher electric field intensities, the required safe distance may extend closer to 2 km to fully comply with ICNIRP safety standards. These suggestion distances are summarized in Table 6, which provides a detailed comparison of field strengths and corresponding safety ranges for each soil type considered in the study.

TABLE 6. Safety distance of vertical electric field (Safe Value: ≤ 5 kV/m)

Type of Soil	GRF	Distance (km)			
		0.8	1.2	1.6	2.0
Sand	0.57	No	Safe	Safe	Safe
Clay	0.94	No	Safe	Safe	Safe
Silt	0.94	No	Safe	Safe	Safe
Gravel	0.61	Safe	Safe	Safe	Safe
Alluvium	0.59	Safe	Safe	Safe	Safe
Peat	0.74	No	Safe	Safe	Safe
Silty Clay	0.97	No	Safe	Safe	Safe

CONCLUSION

This study has thoroughly investigated the behavior of LEMF on overhead distribution lines in Sabah. The findings highlight the importance of considering soil properties, especially GRF when evaluating the LEMF. Their exposure risk near overhead bare conductors affected by lightning as well as the distances. The Gravel (GRF = 0.61) and Alluvium (GRF = 0.59) exhibited lower average vertical electric field values, indicating a safer minimum distance of at least 0.8 km compared to the others. Also, the observed significant reduction in the vertical electric field demonstrates how the field intensity diminishes with increasing distance from the lightning strike point. The exact rate of decrease varies depending on soil resistivity, which influences the propagation and dissipation of the electric field, and consequently affects the magnitude of lightning- induced voltage in the system. These findings provide valuable insights for utility companies in developing strategies to enhance system reliability and protect against transient overvoltages.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the Malaysian Education Ministry for the financial support it provided via the Fundamental Grant Research Scheme (USIM/FRGS/FKAB/FKP/52721).

DECLARATION OF COMPETING INTEREST

None.

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