Effects of Lightning Electromagnetic Field due to Lightning Strikes on a Tall Structure

Norhidayu Rameli*, Mohd Zainal Abidin Abd Kadi, Mahdi Izadi, and Norhafiz Azis

Abstract—It is a fact that tall towers have a high chance of being struck by lightning, resulting in an induced voltage on a piece of a conductor through the coupling effect of the electromagnetic field. As a result, it disrupts the power supply on the distribution power line. This paper proposes new expressions of the lightning electromagnetic field (LEMF) and further investigates their effects due to lightning strikes on a tall structure. The new expression is calculated using trapezoidal and finite-difference time-domain (FDTD) methods and programmed through MATLAB. The expression was verified by literature measurement work and obtained with a reasonably accurate match. Also, the effects of LEMF due to the lightning current front time and the ground impedance were investigated. The result indicated that at least 50% of the LEMF peaks experience a reduction as the current front time increases and declines as the ground impedance increases. Hence, these results significantly impact the assessment of lightning-induced voltages in the distribution power line. It may help determine an appropriate solution for lightning protection, including selecting a line arrester rating, improving the basic insulation level (BIL) and the ground system.

Index Terms—Electromagnetic field, ground impedance, lightning, tall tower

I. INTRODUCTION

The electromagnetic field is an essential component of lightning that contributes to large disturbances in power lines once they couple to conductor lines, resulting in lightning-induced overvoltages (LIOV). According to [1-3], tall towers are likely to be struck by lightning and are estimated to have higher LEMF values than indirect strikes. Therefore, investigating the LEMF effect in the presence of tall towers at close distances becomes essential as it affects the performance of the associated power lines.

LEMF can be calculated using different methods, such as a monopole, dipole, finite-difference time-domain (FDTD), and method of moments (MoM) [4-7]. Each method represents a particular knowledge-based calculation difference, leading to several advantages and disadvantages. In addition, the evaluating LEMF is based on numerical integration and the propagation of lightning current along the channel and tower. This paper proposes new expressions by considering the straightforward numerical integration, which gives accurate results. The validation of the proposed expression is demonstrated by comparing it with the literature measurement work.

Moreover, the proposed expressions are expanded to investigate LEMF effects due to the lightning current front time and ground impedances. The tall tower's ground impedances are the reflection factor parameters that can influence lightning current propagation and LEMF [8,9]. In reality, the ground impedance value depends on various types of grounding arrangements of the tower itself. The relationship between these parameters can cause changes in the ground impedance value, leading to variations in tall towers' ground-reflection factor (GRF) value due to the correlation between the ground impedance and the tower.

Hence, this paper presents a new LEMF expression and the effects of LEMF due to lightning strikes on tall structures. This study may interact with the interest of electrical engineers when considering lightning protection schemes for their systems. It should be emphasized that the LEMF is related to the LIOV resulting from the coupling event. Therefore, any effect on LEMF will, in turn, affect the LIOV.

Some basic assumptions are considered in this paper: 1) the lightning channel is a vertical channel without any branches, and the subsequent return stroke is considered; 2) the tower is lossless and a perfect conductor; and 3) the ground is flat and has perfect soil conductivity.

II. LITERATURE REVIEW

The LEMF can be calculated by considering the lightning current input, which is the channel-base current and the return stroke current [10, 11]. These two currents can be expressed in mathematical expressions in subsections A and B. Subsection C reviewed the expression of the LEMF method.

A. Evaluation of Channel-Base Current

Each lightning channel-base current expression presents some advantages and disadvantages [12,13]. The Bruce-Golde (BG’s) function provides fewer parameters that need to be considered. However, the main problem of the BG’s function is the generation of discontinuity values for the first of current derivatives with respect to the time derivative, $\frac{dv}{dt}$, at time equal...
to zero. The drawbacks of BG’s function are overcome by the other channel-based current function development. The Heidler, Pulse, Diendorfer and Uman (DU), and Nucci’s current function represent the continuity value for the time equal to zero. The current derivative, with respect to the time derivative, will affect the calculation of LEMF and LIOV. Moreover, even though the newly devised current functions have been proposed, several additional parameters have been contributed that may be too complex to be considered in the calculation of LEMF and LIOV. Equation (1) shows the DU expression.

$$i_{subs}(z', t) = \left[ \frac{i_{o1}}{\eta_1} \frac{z'}{c} \right] + \frac{i_{o2}}{\eta_2} \frac{z'}{c} \exp \left( -\gamma t \right)$$

(1)

Where $i_{o1}$ and $i_{o2}$ are the amplitude of the channel base current, $\Gamma_{11}$ and $\Gamma_{12}$ are the front time constants, $\Gamma_{21}$ and $\Gamma_{22}$ are the decay-time constants, $\eta_1$ and $\eta_2$ are exponents in the range of 2–10 and $h_1$, $h_2$ are the amplitude correction factors.

### B. Evaluation of Lightning Return Stroke

Once lightning has struck the top of a tower, the lightning current begins to propagate upward through the lightning channel at return stroke velocity speed and downward through the tower path at the speed of light as shown in Fig. 1. The channel-base current is presented in the mathematical expression in Subsection A. Both of these currents experience a reflection event. However, the first lightning current striking the top of the tower is assumed to be undisturbed and not influenced by any reflection event.

As reviewed and discussed by [13-15], the lightning return stroke current can be evaluated along the channel and tower by considering the effect of multiple reflections and the reflection coefficient of the tower. A few mathematical models can express this situation. The models are identical to each other apart from the differences in defining the term for the injected lightning current. Equations (2) to (3) describe the lightning return stroke current along the channel and tower, respectively.

$$i(z', t) = P(z' - h) i_0 \left( h, t - \frac{z' - h}{c} \right) - \gamma_1 i_0 \left( h, t - \frac{z' - h}{c} \right)$$

(2)

The distribution current along the channel $h < z' < H$

$$i(z', t) = (1 - \gamma_1) \sum_{n=0}^{\infty} \gamma_n i_0 \left( h, t - \frac{z' + h}{c} - \frac{2nh}{c} \right)$$

(3)

The distribution current along the tower $0 \leq z' \leq h$

Where $\gamma_1$ and $\gamma_2$ are the top and ground current reflection coefficients, respectively, $n$ is the number of reflection currents inside the tower, $h$ is the tower’s height, $i_0$ is a current function, $c$ is the speed of the upward lightning channel for the waves that propagate in the lightning channel, $P(z' - h)$ is the model-dependent attenuation function and $u(t)$ is the Heaviside unit-step function. It should be noted that $P(z' - h)$ is a model-dependent attenuation function known as the return stroke current model as presented in Table I.

### TABLE I

MODEL-DEPENDENT ATTENUATION FACTOR BASED ON THE RETURN STROKE CURRENT MODEL [11, 16]

<table>
<thead>
<tr>
<th>Return stroke current model</th>
<th>$\nu$</th>
<th>$P(z')$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bruce-Golde, BG</td>
<td>$\infty$</td>
<td>1</td>
</tr>
<tr>
<td>Traveling Current Source, TCS</td>
<td>$-c$</td>
<td>1</td>
</tr>
<tr>
<td>Transmission Line, TL</td>
<td>$\nu$</td>
<td>1</td>
</tr>
<tr>
<td>Modified Transmission Line with Exponential Decay, MTLE</td>
<td>$\nu$</td>
<td>$\exp (-\frac{z'}{\lambda})$</td>
</tr>
<tr>
<td>Modified Transmission Line with Linear Exponential Decay, MTLL</td>
<td>$\nu$</td>
<td>$1 - \frac{z'}{H_{TOT}}$</td>
</tr>
</tbody>
</table>
This model affects the lightning return stroke current along a channel as described in (2). This paper employs the Transmission Line (TL) model to describe the return stroke current along the lightning channel. The TL model is used because it can estimate the initial field peak for the initial period and provides the simplest mathematical model [16].

Furthermore, as presented in (2) and (3), both of the lightning return stroke currents are dependent on the input of the injected lightning current (channel-base current) and the reflection coefficient factor (RCF) parameters. Hence, both currents can be observed based on the variation in the value of the current front time for the lightning current injection (channel-base current), which can be described as a “speedy,” “fast,” or “slow,” current front time. Also, the effect of the variation in the value of the ground impedance, particularly for the GRF for the RCF on the LEMF, is obtainable. It should be noted that the ground impedances are accounted by the circular grounding arrangement as presented in (4) with different levels of soil resistivity as presented in Table II [17]. In this paper, the soil resistivity values were selected as 30 Ω.m, 80 Ω.m, 130 Ω.m, 2 kΩ.m, 10 kΩ.m, and 20 kΩ.m.

\[ z_g = \frac{1}{n} \rho \ln\left[ \frac{4L}{a} \right] - 1 + \frac{L}{S} \left( \ln \frac{2n}{\pi} \right) \]  

(4)

Where \( \rho \) is the soil resistivity, \( n \) is the number of rods, \( L \) is the conductor length, \( a \) is the conductor radius and \( S \) is the space between two rods.

C. Evaluation of Lightning Electromagnetic Field

Once a tower is struck by lightning, the LEMF responses are created. In mathematical modeling, the LEMF response can be determined by calculating the lightning current distribution along the channel and tower, \( i(z', t) \) at an observation point, \( z_o \), a few meters separated from the tall tower, \( r \) and \( h \) height of tall tower, as presented in Fig. 2. Several methods can be employed to calculate the LEMF, such as monopole, dipole, FDTD, and Hybrid [18,19]. The monopole method is a method that considers the current and charge densities as a function of time and space. This method is primarily used and can be applied to simple lightning models. In addition, dipole is a method that considers the lightning current as a function of time and position. Hence, this model is suitable for straightforward applications using the return stroke current. Also, this model represents different terms of the LEMF concerning various range dependencies, which allows the researcher to simplify the work based on the specific range. Table III summarizes the calculation knowledge method, advantages, and disadvantages.

III. METHODOLOGY

A detailed explanation regarding the method of this work is presented in this section. It comprises an evaluation of the lightning return stroke current due to the channel and the tower as well as proposing a new expression of the LEMF.

A. Channel-Base Current

The work begins with the evaluation of the channel-base current. In the presence of a tall tower, the channel-base current is seen as an undistributed current, \( i_o(t) \), which is assumed to be an ideal current, with both of the reflection coefficients for the tower equal to zero and the return stroke wavefront reflections being disregarded. Hence, the channel-base current...
can be seen as an injected lightning current, \( i_0(t) \), at the top of the tower. In this work, the DU channel-base current is selected to model the injected current at the top of the tall tower due to the ability of this current function to present a similar waveshape of the measured current. The expression of DU function is shown in Subsection A, (1).

### B. Return Stroke Current and Verification

As reviewed in Subsection B (in Literature Review), an engineering model based on a distributed source representation expressed by (2) and (3) was adopted in this work. This model provides a straightforward formulation in which the specific channel-base current function, current distribution along the channel and the tower, and return stroke current model are considered. In addition, the return stroke current model of the MTLE model was selected to describe the return stroke current along the lightning channel, which represents a decreasing current in the exponential factor at an increasing channel height. The mathematical expressions of the channel-base current and return stroke current were programmed and validated with the measured data found in the literature [20]. Fig. 3 presents the validation work whereby a good agreement was observed between the measured and simulated waveshape.

#### C. A New LEMF Expression and Verification

In addition, the work continues by proposing a new LEMF expression using the dipole and FDTD methods known as a Hybrid solution. An equation of LEMF of the dipole method as presented in Eqs. (5) to (7) was used as basic of LEMF equations.

\[
\mathbf{B}_0 (r, z, t) = \frac{\mu_0}{4\pi} \left[ \int_{-H}^{H} \frac{r}{R^3} i \left( z', \tau - \frac{R}{c} \right) \, dz' + \int_{-H}^{H} \frac{r}{cR^2} \frac{\partial (z', t - \frac{R}{c})}{\partial t} \, dz' \right]
\]

\[
\mathbf{dE}_z (r, z, t) = \frac{1}{4\pi\varepsilon_0} \left[ \int_{-H}^{H} \frac{2(\tau - z')^2 - r^2}{R^5} i \left( z', \tau - \frac{R}{c} \right) \, dr \, dz' + \int_{-H}^{H} \frac{2(\tau - z')^2 - r^2}{cR^4} i \left( z', t - \frac{R}{c} \right) \, dz' - \int_{-H}^{H} \frac{r}{cR^2} \frac{\partial (z', t - \frac{R}{c})}{\partial t} \, dz' \right]
\]

\[
\mathbf{dE}_r (r, z, t) = \frac{1}{4\pi\varepsilon_0} \left[ \int_{-H}^{H} \frac{3(\tau - z')^2 - r^2}{R^5} i \left( z', \tau - \frac{R}{c} \right) \, dr \, dz' + \int_{-H}^{H} \frac{3(\tau - z')^2 - r^2}{cR^4} i \left( z', t - \frac{R}{c} \right) \, dz' - \int_{-H}^{H} \frac{r}{cR^2} \frac{\partial (z', t - \frac{R}{c})}{\partial t} \, dz' \right]
\]

Where \( r \) is the radial distance, the observation height, \( z' \), the height of the return stroke path is \( R \), the distance between the height at the return stroke path and the observation point is \( R = \sqrt{r^2 + (z' - z)^2} \), \( c \) is the speed of light, \( \varepsilon_0 \) is the permittivity of free space, \( \mathbf{H} \) and \( -\mathbf{H} \) are the integral limit on the real and image, respectively.

Moreover, for solving the non-integral function, \( \mathbf{i}(z', t) \) as presented in (2) and (3), numerical integration is applied. In this work, the trapezoidal numerical integration solution was used. This solution provides a straightforward formulation and gives a good result compared with the measured value. The derivative electric fields were calculated as expressed in (8) to (9).

\[
\mathbf{dE}_z (r, z, t_n) = \sum_{m=0}^{k} \left\{ a_{cr,m} F(x, y, z, t = t_n, z' = H_{cr,m}) - a'_{cr,m} F(x, y, z, t = t_n, z'' = H_{cl,m}) \right\}
\]

\[
\mathbf{dE}_r (r, z, t_n) = \sum_{m=0}^{k} \left\{ a_{cr,m} F(x, y, z, t = t_n, z' = H_{cr,m}) - a'_{cr,m} F(x, y, z, t = t_n, z'' = H_{cl,m}) \right\}
\]

where \( a'_{cl,m} \) and \( a'_{cr,m} \) are the coefficients of trapezoid respecting the channel for real and image at the number of trapezoid segments, \( H_{cr,m} \) and \( H'_{cl,m} \) is an integral limits respecting to channel for real and image at different height of the channel path as well at the number of trapezoid segment, \( F \), the elemental current, \( \mathbf{i}(z', t) \) along the channel and \( t_n \) is the time, \( t_n = (n - 1)\Delta t \), \( n = 1, 2, \ldots n_{max} \).

The FDTD method was employed in (8) and (9) to solve the derivative of the electric fields, \( \frac{\partial \mathbf{E}}{\partial t} \), whereby layer by layer, the electric fields were calculated. In addition, the vertical electric field is a significant field that should be determined when considering the coupling evaluation. Fig. 4 shows the validation result of the vertical electric field, 185 m from the tower. Moreover, the wave shape between the simulated and measured values is in good agreement, and the percentage differences are less than 10%.
Overall, the vertical electric fields exhibited good agreement with the measured values. The percentage difference between these values for first of 2 µs is in the acceptable range at less than 10%, and the wave shape of the result is seen to be practically the same as the measured values.

Fig. 4. Comparison between the measured and simulated vertical electric field at 185-m distance from Peissenberg tower

D. Lightning Current Front Time and Ground Impedances

The parameter values of (1) were varied to generate a different lightning current front time, as expressed in Fig. 5. The front time was classified as “very fast,” “fast,” or “slow” at 0.15 µs, 0.70 µs, and 1.20 µs, respectively. Moreover, as shown in (4), the ground impedance was varied based on a circle grounding arrangement and soil resistivity as tabulated in Table II, and the tower impedance was assumed to be 180 Ω. The ground impedance was defined as having a low or high value, as shown in Table IV.

Fig. 5. Lightning current for different values of the front time

<table>
<thead>
<tr>
<th>Table IV</th>
<th>VARIATION OF GROUND IMPEDANCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower impedance (Ω)</td>
<td>Ground impedance (Ω)</td>
</tr>
<tr>
<td>180</td>
<td>2.88</td>
</tr>
<tr>
<td></td>
<td>7.70</td>
</tr>
<tr>
<td></td>
<td>12.51</td>
</tr>
<tr>
<td></td>
<td>192.46</td>
</tr>
<tr>
<td></td>
<td>962.29</td>
</tr>
<tr>
<td></td>
<td>1924.57</td>
</tr>
</tbody>
</table>

Fig. 6. Vertical electric field for different lightning current front times and GRF at a 20-m distance from the struck tower; a) front time $t_f=0.15$ µs, (b) $t_f=0.70$ µs, and (c) $t_f=1.2$ µs

IV. RESULT AND DISCUSSION

Effects of vertical electric field due to lightning current front time and ground impedances

The wave shape of vertical electric field as shown in Fig. 6 was observed. Result indicates that a non-fluctuation in the wave shape for the initial time was observed for an increasing current front time and ground impedance. This was due to the simulated field at a very close distance in which the electrostatic effect dominated instead of induction or radiation. However, flattening of the fields occurred during the tail time.
In addition, the field peak demonstrated a reducing trend as the current front time and ground impedance increased, as presented in Table V. By referring to the value at a current front time of 0.15 μs and a ground impedance of 2.88 Ω, the vertical electric field was reduced from 809.70 kV/m to 338.90 kV/m, which is equivalent to at least 0% to 58.16% as the current front times increase. However, the percentage reduction of the peaks increased as the ground impedances varied. The field peaks were reduced from 0.89% to 58.91% for the case of low ground impedance, equivalent to 802.70 kV/m to 332.80 kV/m. For the high impedances, the percentage reduction in the field peaks became more apparent at 25.9% to 91.50%, equivalent to 600.10 kV/m to 68.88 kV/m.

TABLE V
VerticaL ELECTric FIELD PEAK VALUES

<table>
<thead>
<tr>
<th>Front time (μs)</th>
<th>Vertical electric field peak (kV/m)</th>
<th>Ground impedance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>809.70</td>
<td>338.90</td>
</tr>
<tr>
<td>0.70</td>
<td>795.70</td>
<td>332.80</td>
</tr>
<tr>
<td>1.20</td>
<td>792.70</td>
<td>600.10</td>
</tr>
<tr>
<td>0.15</td>
<td>709.70</td>
<td>291.40</td>
</tr>
<tr>
<td>0.70</td>
<td>689.20</td>
<td>177.90</td>
</tr>
<tr>
<td>1.20</td>
<td>658.90</td>
<td>115.00</td>
</tr>
</tbody>
</table>

Overall, the results indicated that the lightning current front time and ground impedance affect the wave shape of the LEMF in the case of striking a tall tower. The wave shapes of the vertical electric field was hardly affected. The wave shape fluctuated in “speedy” and “fast” front times cases, and the wave shape was slightly smooth for the “slow” front time cases. Moreover, different ground impedances tended to generate various wave shapes. Multiple field peaks were observed for low values of ground impedance and slightly reduced for high values of ground impedance. However, in all cases, a very smooth wave shape could be observed for the 192 Ω ground impedance. Furthermore, the lightning current front time and ground impedance strongly affected the field peak for all the LEMFs. The field peak reduced as the front time and ground impedances increased, suggesting the following:

1) At least in the 0% to 58% range, all the peaks showed a reduction for an increasing lightning current front time and the lowest ground impedance.

2) At least in the 30% to 91% range, all the peaks showed a reduction for the highest ground impedance.

Hence, this study can be helpful for electrical engineers to decide on the appropriate protection for evaluating the LIV when the LEMF has interacted with the conductor line in which the factor of the lighting current front time and the variation in the value of the ground impedances need to be considered.

V. CONCLUSION

In this paper, the effects of LEMF due to the lightning strike to a tall structure have been investigated, and the results are discussed accordingly. The results indicate that the lightning current front time and ground impedance significantly affect the wave shape and value of the LEMF. The wave shape and value fluctuation slightly reduce as the lightning current front time increases. Also, the wave shape of the LEMF delivers a smooth wave shape and shows a reduced peak for an increase in ground impedance. Therefore, the influence of the lightning current front time and ground impedance on the LEMF should be considered when predicting the LEMF, which may be affected when evaluating the LOIV and is known as a major issue for power distribution lines.

REFERENCES

