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Effect of Soil Resistivity on Magnetic Field in the case of Lightning Strike to a Tall Structure

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***Abstract*— When a tower is struck by lightning, an induced voltage can generate in conducting objects within its vicinity. This phenomenon is due to the interaction between the electromagnetic field of the lightning with the object. The magnetic field is part of this field. Previous studies have shown that the magnetic field is affected by ground reflection coefficient factors that are usually taken as constants. However, the ground reflection coefficient factors have correlation with tower and ground impedance whereby the ground impedance can be determined based on soil resistivity and grounding system. This paper investigates the effect of soil resistivity on the value of magnetic field for a case of lightning strike on tall structures. Lightning current has been modelled accordingly and a set of equations is proposed to evaluate the magnetic field. Also, the effects of soil resistivity on the value of ground reflection coefficient factor consequently of the magnetic peak have been investigated. The results indicate that the magnetic field changes substantially with a variation of the soil resistivity. The magnetic field peak also has a strong correlation with the changes of soil resistivity as well as the fast front time of the channel base current. The outcome of the result of this paper will be beneficial to utility companies in determining the appropriate level of lightning protection since the magnetic field will be a result of induced voltage when have interaction with power lines.**

Keywords-component; lightning, tower, magnetic field, soil resistivity, ground reflection factor

I. Introduction

A direct lightning strike to a tower may generate transient overvoltage in conducting objects within its vicinity. This phenomena is a result of the coupling of lightning electromagnetic fields with objects [1] which may cause equipment damage [2]. The magnetic field is a part of this electromagnetic field. According to [3-5], the magnetic field is influenced by few parameters such as the front time of the current, the tower height, the return stroke velocity and the reflection coefficient factors. Among these parameters, the reflection coefficient factors seem to have the most influence on the wave shape and peak [6-9]. It is because the tall structure height is more than 100 m height and it is experience to have reflection phenomena of lightning current inside the structure. The ground reflection coefficient is one such factor whereby it is dependent on the difference in the impedance between the tower and ground. By maintaining a constant tower impedance, the ground impedance can be determined through the relationship with the soil resistivity and grounding arrangement [10]. Thus, the ground impedance can have a variety value and it is effect on the value of ground reflection coefficient factor whereby to date, most researchers assume a constant value for this coefficient. Therefore, the aim of this paper is to investigate the effect of soil resistivity on the value of magnetic field for a case of lightning strike on a tall structure. The outcome of this paper may beneficial to the utility companies in setting the appropriate level of lightning protection since the magnetic field will result of induced voltage when having an interaction with power line. Some basic assumptions are made as listed:

1- The lightning channel is formed by a perpendicular strike to the tower without any branches.
2- The tower is uniform and located on a flat ground surface.

II. Lightning Return Stroke Current Along The Channel And Tall Structure

The lightning return stroke current is the most important aspect that needs to be evaluated. It consists of the channel base current as well as the current along the channel and the tower at different heights. The channel base current is one the first parameters that can be determined via measurement [7]. However, in mathematical modelling, the channel base current can be represented reasonably well through several functions. Each function describes particular characteristics of the lightning current which rely on specific parameter values [11-15]. One of the simplest channel base current functions typically used for the sake of simplicity is the Bruce-Golde (BG) function. However, the weakness of the BG function is providing a zero value for $\partial i / \partial t$ in the early time periods also, providing non-fluctuation responsiveness during the tail time which makes it only suitable to simulate the initial time. In this paper, the BG function is applied using Eq. (1) where i_o is the amplitude of the channel base current and α and β are the constant factors. The amplitude was simulated for the first 10 µs using the parameters given in Table I. Moreover, Fig. 1 shows a comparison between the BG function and the channel base current measured at the top of a Gaisberg tower measured at 20m from an observation point [7]. It shows that the BG function is a close approximation to the channel base current within an acceptable percentage range as given in Table II as well as the wave shape which is in good agreement with the measured shape.

$$I_o(0,t) = i_0\left(e^{-\alpha t} - e^{-\beta t}\right) \quad (1)$$

TABLE I. PARAMETER VALUES FOR THE BG FUNCTION

Parameter Simulation	
Current peak, i_o(kA)	15.83
Constant factor, α(1/s)	13.58×10^4
Constant factor, β(1/s)	66.46×10^5

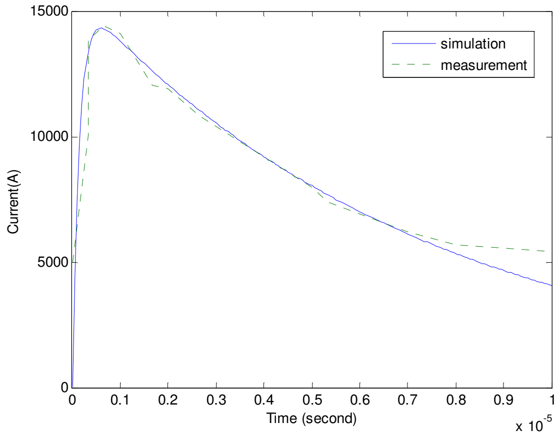

Figure 1. A comparison between the BG function and the measured channel base current at the top of Gaisberg tower, 100 m.

TABLE II. A COMPARISON OF THE CHANNEL BASE CURRENT BETWEEN SIMULATION AND MEASUREMENT

Time, µs	0.33	0.67	1.00	2.00	5.00	7.00	8.00
Current (Measured),kA	13.65	14.42	14.09	11.92	0.79	0.62	0.56
Current (Simulated),kA	13.37	14.28	13.80	12.07	0.80	0.61	0.53
Percentage difference,%	2.07	0.98	2.07	1.25	1.25	1.37	6.00

Furthermore, several models have been proposed to evaluate the lightning current along a channel and a tower[16-19]. In this paper, the engineering model is used as given in Eq. (2)[20]where $P(z'-h)$ is the model-dependent attenuation function, h is the tower height, v is the return stroke velocity, c is the speed of light, γ_t is the top reflection coefficient factor, γ_g is the ground reflection coefficient factor, n is the number of the reflection event and $u(t)$ is the Heaviside function. It represents the lightning current evaluated at different heights of the channel. The Transmission Line (TL) current model is used as it represents the model-dependent attenuation function. This selection is based on the behaviour of the magnetic field peak itself which not affected by the return stroke model selection [7, 17]. On the other hand, Eq. (3) shows the lightning current distribution along the tower. It is noted that this current is independent of the return stroke current model, but strongly depends on the reflection event.

$$i(z',t) = \left[P(z'-h)I_o\left(h, t-\frac{z'-h}{v}\right) - \gamma_t I_o\left(h, t-\frac{z'-h}{c}\right) + (1-\gamma_t)(1+\gamma_t)\sum_{n=0}^{\infty}\gamma_g^{n+1}\gamma_t^{n} I_o\left(h, t-\frac{h+z'}{c}-\frac{2nh}{c}\right)\right] u\left(t-\frac{z'-h}{v}\right) \quad (2)$$

$$i(z',t) = (1-\gamma_t)\sum_{n=0}^{\infty}\left[\gamma_g^{n}\gamma_t^{n} I_o\left(h, t-\frac{h-z'}{c}-\frac{2nh}{c}\right) + \gamma_g^{n+1}\gamma_t^{n} I_o\left(h, t-\frac{h+z'}{c}-\frac{2nh}{c}\right)\right] u\left(t-\frac{h+z'}{c}-\frac{2nh}{c}\right) \quad (3)$$

III. GROUND REFLECTION COEFFICIENT FACTOR

The ground reflection coefficient factor has a correlation between the tower and ground impedance as expressed in Eq. (4).

$$\gamma_g = \frac{z_t - z_g}{z_t + z_g} \quad (4)$$

By maintaining a constant value for the tower impedance, the ground impedance can be determined through a relationship with the grounding arrangement, of which the soil resistivity value is the dependent factor on that arrangement[21]. In this paper, a circular grounding arrangement is selected as expressed in Eq. (5) and the parameters are considered as stated in [10, 22, 23].

$$z_g = \frac{1}{n}\frac{\rho}{2\pi L}\left[\left(ln\frac{4L}{a}\right) - 1 + \frac{L}{S}\left(ln\frac{2n}{\pi}\right)\right] \quad (5)$$

Where: ρ is a soil resistivity, n are a number of rods, L is a conductor length, a is a conductor radius and S is a space between two rods.

On the other hand, different values of soil resistivity can be selected based on typical values of soil type [24] whereas the soil resistivity value of 20,000 Ω.m is in categories of calcareous remains soil as tabulated in Table III.

TABLE III. THE TYPE AND VALUES OF THE SOIL RESISTIVITY

Type of soil	Soil resistivity range, Ω.m
Lake and river water	100-400
Commercial distilled water	1000-4000
Clay	25-100
Sandy clay	40-300
Peat, marshy soil	50-300
Limestone	100-5000
Sand, granites	100-10,000
Moraine	1000-10,000
Calcareous remains	3000-30,000

The value of the ground reflection coefficient factor against soil resistivity was plotted in reference [10]. The results indicated that the ground reflection coefficient factor had a reducing trend with a non-linear behaviour with respect to increasing soil resistivity. This reducing trend is cause by the value of ground impedance whereby as increase the ground impedance and maintaining the tower impedance, the ground reflection factor will be reduced. Noted, this trending is same for all cases of grounding arrangement; vertical, horizontal and grid grounding arrangement.

IV. CALCULATION OF THE MAGNETIC FIELD

Magnetic fields at an observation point can be calculated by considering an element of current, $i(z',t)$ along the vertical axis of the channel path as well as on the tower as shown in Fig. 2. The observation point was located at a certain height from the flat ground surface and few metres distant from the tower struck by lightning.

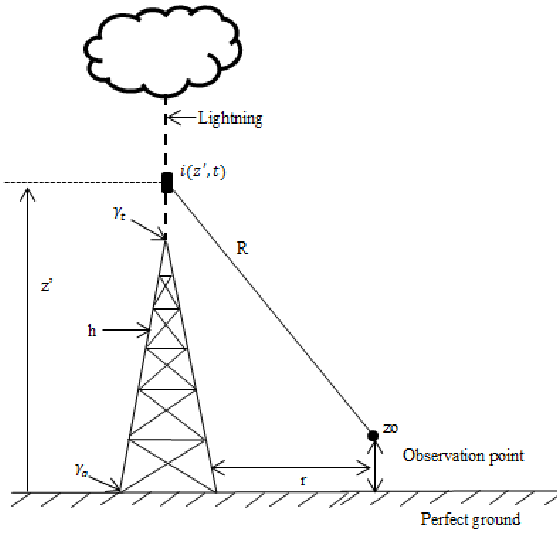

Figure 2. Geometry for the calculation of the magnetic field with respect to a lightning strike on a tower

The well-known equation for calculating the magnetic field is presented in Eq. (6) [25], where r is the radial distance between the channel and the observation point, zo is the observation point height, R is the distance between the dipole current and the observation point, $R = \sqrt{(z'-zo)^2 + r^2}$, c is the speed of light and $i(z',t)$ is the elemental current along the channel-tower.

$$H_{\emptyset}(r,zo,z',t) = \frac{\mu_o}{4\pi}\int_{z'}^{z}\left[\frac{r}{R^3}i\left(z',t-\frac{R}{c}\right) + \frac{r}{cR^2}\frac{\partial i\left(z',t-\frac{R}{c}\right)}{\partial t}\right] \qquad (6)$$

Thus, by solving the integral limit for the channel-tower real and image with respect to the changes in height along the channel and at the top of the tower height which based on retardation concept [26], the total magnetic field can be calculated. However, the elemental current, $i(z',t)$ is unable to be integrated by a straight forward procedure where normally the numerical method of integration would be employed [27, 28]. In this paper, the numerical Trapezoid method is applied since it provides an accurate result. Therefore, by considering Eq. (1) to (6), the total magnetic field can be obtained through Eq. (7).

$$H(r,z,t_n) = \sum_{m=0}^{k}\left\{a_{cr,m}F\left(t=t_n, z'=H_{cr,m}\right) - a'_{ci,m}F\left(t=t_n, z''=H_{ci,m}\right)\right\} + \left\{a_{tr,m}F\left(t=t_n, z'=H_{tr,m}\right) - a'_{ti,m}F\left(t=t_n, z''=H_{ti,m}\right)\right\} \qquad (7)$$

Where:
$a_{cr,m}$ and $a'_{ci,m}$ is a coefficient of trapezoid respecting to channel for real and image at number of trapezoid segment.
$a_{tr,m}$ and $a'_{ti,m}$ is a coefficient of trapezoid respecting to tower for real and image at number of trapezoid segment.
$H_{cr,m}$ and $H'_{ci,m}$ is an integral limit respecting to channel for real and image at different height of channel path as well at number of trapezoid segment
$H_{tr,m}$ and $H_{ti,m}$ is an integral limit respecting to tower for real and image at top of tower height as well at number of trapezoid segment.
Noted, the number of trapezoid segment should more or equal to 2 (k≥2).
F is the elemental current, $i(z',t)$ along the channel-tower.
t_n is the time, $t_n = (n-1)\Delta t \; n = 1,2,\ldots n_{max}$

Moreover, the accuracy of the result of magnetic field modelling strongly depends on the selected value of Δt as well as a higher value of k[12, 29]. In this paper, the Δt and k were set at 0.5×10^{-7}s and 82, respectively.

Fig. 3 shows a comparison between the simulated magnetic field and the measured field for the first 15 µs. The simulation results show good agreement with the measurements whereby the percentage difference is less than 10% difference and within the acceptable range as tabulated in Table IV. Hence, the result validation indicates that the proposed equation is reasonably accurate. Noted, in order to increase the accuracy of result, the value of Δt and k can change directly from the proposed equation. The magnetic field was measured at a close distance of 20 m from the tower of height 100 m at an observation point with a height of 3 m [7].

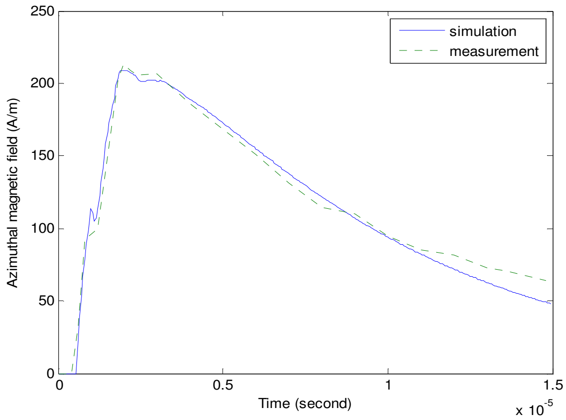

Figure 3. A comparison between the magnetic field simulation and measurement at distance of tower axis, 20 m.

TABLE IV. A COMPARISON OF THE MAGNETIC FIELD BETWEEN SIMULATION AND MEASUREMENT

Time, µs	2.00	4.00	6.00	8.00	10.00
Magnetic (Measured),A/m	213.20	186.20	150.70	114.50	94.74
Magnetic (Simulated), A/m	209.10	189.20	154.90	121.70	93.96
Percentage difference,%	1.90	1.59	2.75	6.09	0.82

V. RESULTS AND DISCUSSION

In order to evaluate the effect of soil resistivity on the value azimuthal magnetic field for a case lightning strike on a tall structure, a different of soil resistivity are considered as well as its effective value on the ground reflection coefficient factor as tabulated in Table V.

TABLE V A VALUE OF SOIL RESISTIVITY AND ITS EFFECTIVE VALUE ON THE GROUND REFLECTION COEFFICIENT FACTOR

Soil resistivity, Ω.m	Ground reflection coefficient factor
30	0.9957
80	0.9886
130	0.9816
2000	0.7490
10000	0.1644
20000	-0.1787

The effect of changes in these values will also be observed on the responsiveness of the magnetic field behaviour at different radial distances of 20 m, 40 m and 80 m as well as on the changes of the front time channel base current. The front time of the channel base current is chosen as 0.15 µs, 0.30 µs and 0.60 µs, and the rest of the tail time of the channel base current is fixed.

Fig.4 illustrates the effect of soil resistivity value on the wave shape of the magnetic field at 20 m distance from the tower struck by lightning. The three lowest and highest values of soil resistivity were selected to observe the responsiveness of the magnetic field. The behaviour of the magnetic fields is non-linear with respect to soil resistivity changes. The results show that at the three lowest soil resistivity values, the magnetic field wave shape shows significantly attenuation and producing the highest magnetic field peak for the lowest of soil resistivity, 30Ω.m. However, for the three highest values of soil resistivity, the magnetic field wave shape indicated a smooth wave shape at 2 kΩ.m and a quickly dissipating attenuated wave shape for the rest of the higher values of soil resistivity. Also, the lowest value of magnetic field peak is showed at the highest of soil resistivity, 20 kΩ.m. The attenuation of the magnetic field wave shape was caused by the positive trend value of the differences between the tower and the ground impedance by means of the ground reflection coefficient factors. It was noted that the ground reflection coefficient factors against the soil resistivity showed a different trend whereby for a soil resistivity less than 10 kΩ.m, the ground reflection factors showed a positive trend value. On the other hand, at 20 kΩ.m of soil resistivity, the ground reflection coefficient factors indicated a negative trend value (as stated in [10], Fig. 4). Hence, the ground reflection coefficient factor needs to have a variation value by means of different soil resistivity relation instead of constant. Result indicates that behaviours as shown in Figure 4 should be taken into account when measuring the magnetic field since the soil resistivity value has a significant effect on the wave shape as well as on the peak value. On the other hand, this situation seems to agree with the behaviour of the lightning current at the top of tower with respect to changes in soil resistivity (as stated in [10], Fig. 6). Thus, it indicates that the magnetic field behaviour is strongly dependent on the lightning current. Hence a sensitivity parameter such as the soil resistivity that influences the lightning current needs to be taken into account in order to accurately determine the magnetic field behaviour.

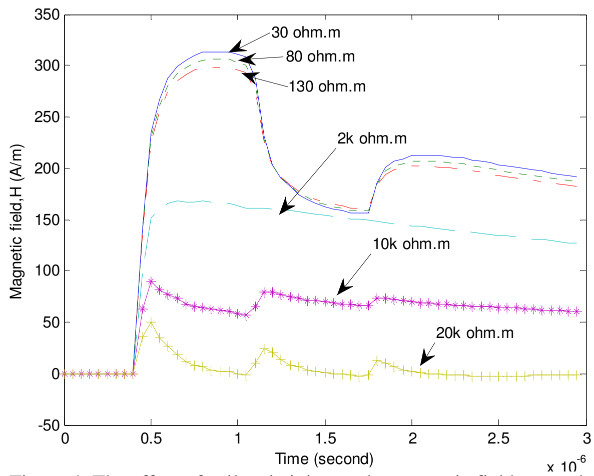

Figure 4. The effect of soil resistivity on the magnetic field wave shape (h=100m, zo=10m,r=20 m, t_f =0.15 µs)

Furthermore, Fig. 5 shows the magnetic field peak for changes in soil resistivity at a close distance of 20 m, 40 m and 80 m from a tower struck by lightning. The behaviour of the magnetic field peak is a non-linear response with respect to the changes in soil resistivity. The magnetic field peak shows a decreasing trend with increasing soil resistivity as well as radial distance. At least more than 50 % of the magnetic field peak at the higher soil resistivity is reduced with respect to the low soil resistivity for all radial distances. Also, less than a 50 A/m magnetic field peak was found for the higher soil resistivity, particularly for a soil resistivity of more than 10 kΩ.m at a radial distance of 40 m, and more than 5 kΩ.m at a radial distance of 80 m. Hence, this result indicates that the highest soil resistivity of at least 5 kΩ.m at a far distance from the tower struck by lightning seems to have little influence on the magnetic field. Thus, it is beneficial to utility companies to consider this behaviour when dealing with the lightning protection scheme by means of induced voltage when the magnetic field is considered to be coupled with the power line.

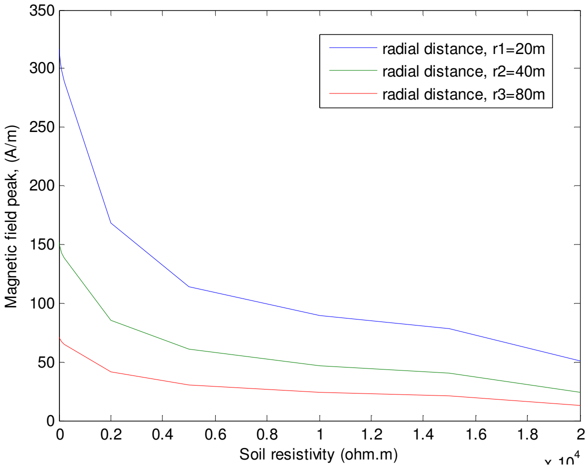

Figure 5. The effect of soil resistivity on the magnetic field peak for different radial distances from the tower struck by lightning (h=100m, zo=10m, t_f =0.15 µs)

Moreover, Fig.6 indicates the effect of radial distance and front time on the magnetic fields respecting to soil resistivity. Overall, the magnetic field peak has non-linear behaviour on the effect of radial distance and front time with respect to soil resistivity. A decreasing trend of magnetic field peak was observed for an increasing radial distance as well as the front time. The results show a reduction of at least 50 % of the magnetic field peak for an increasing radial distance for all variations in soil resistivity. On the other hand, the magnetic field peak shows a decreasing trend of up to 40 % for increasing front time with respect to the fast front time of 0.15 µs for changes in soil resistivity. In addition, less than a 50 A.m magnetic field was found when the soil resistivity was more than 15 kΩ.m at 20 m distance with respect to the increasing front time. However, similar values for the magnetic field were found for different values of soil resistivity with distance. For example, at 40 m distance, less than 50 A.m was found for a soil resistivity of more than 10 kΩ.m and this reduced to 5 kΩ.m as the front time increased. Also, the soil resistivity was found to have less effect on the magnetic field peak for all values of soil resistivity and increasing front time at 80 m distance. Therefore, the magnetic field peaks appear to be less affected by the soil resistivity as the radial distance increases as well as the front time. Hence, this behaviour needs to be taken into account by the utility companies when selecting an appropriate location for a tower.

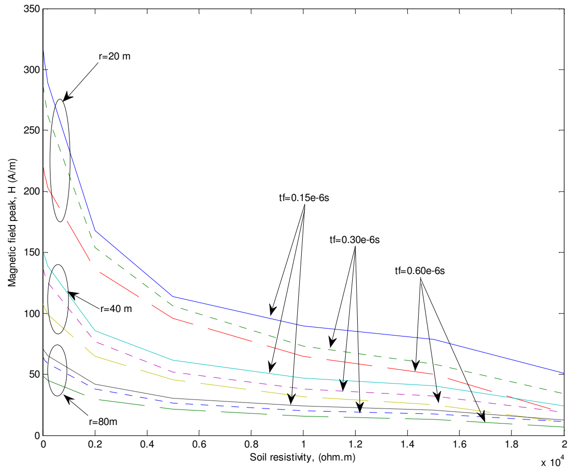

Figure 6. The effect of changes in soil resistivity on the magnetic field peak for different radial distances and front times(h=100 m, zo=10 m)

Overall, the behaviour of the magnetic field peaks was non-linear with increasing soil resistivity, radial distance and front time of the channel base current. An attenuation wave shape for the magnetic field was observed at the lower values of soil resistivity and quickly dissipated at the higher soil resistivity values. Also, the magnetic field peak was found to indicate a reducing trend for increasing radial distance and front time with respect to changes in soil resistivity. The effect of soil resistivity on the responsiveness of the magnetic field was found to be significant for very close distances and fast front times. Noted that, the magnetic fields are not much affected by the ground conductivity [30].

VI. CONCLUSION

The effect of soil resistivity on the value of magnetic field in the case of lightning strike on the tall structure was considered accordingly. The results show that the magnetic field peak is greatly affected by changes in the soil resistivity. Also, the magnetic field peak was found to be most influenced by the soil resistivity at a very close distance as well as by fast front times. Thus, it is important to consider the soil resistivity when evaluating the magnetic field behaviour. Should be reminded that, the soil resistivity makes a variable value on the ground impedances and its effective value made a variation value on the ground reflection coefficient factor, consequently the magnetic field will be affected. Therefore, this result may useful in deciding the lightning protection scheme when this field becomes interaction with the power line as a lightning induced voltage.

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