Numerical Electromagnetic Analysis of GSM Tower under the Influence of Lightning Over-voltage

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Abstract – In the last twenty years, the widespread use of sensitive electronic devices in telecommunication systems and power systems has increased the interest in transients, in particular those caused by lightning (direct and/or indirect) strokes. Lightning over-voltage causing unpredictable and accidental interruption in these systems is a very important factor also in telecommunication systems and transmission lines. So the electromagnetic interference (EMI) analysis of different communication towers under the influence of lightning over-voltage on tall structures is necessary to avoid these unexpected interruptions. This paper presents a numerical electromagnetic simulation of direct lightning stroke for the EMI analysis of a GSM tower utilizing Method of Moments. This analysis is also a primary factor and can give approximate solution, helpful for correct EMC design of transient protection circuits for GSM base-station.

I. INTRODUCTION

The prediction of lightning-induced over-voltage on tall structures like communication towers is important, which is motivated by the widespread use of sensitive electronic devices in telecommunication systems and data transmission networks. From this point of view, transients caused by lightning (direct and/or indirect) can be one of the major causes of malfunction, or even destruction, of electronic equipment of the installations. In particular, Lightning over-voltages which can cause disruption in the telecommunication or data-transmission networks, or sudden micro-interruptions of the power supply during thunderstorms have been seriously reconsidered, due to the increasing demand for good quality and reliability in the transmission of information.

There is no clear evidence in the literature of the relationship between the number of outages during thunderstorms and lightning-flash density in the proximity of the place of failure. However a report shows that more than 27% failure of electronic components is caused by over-voltages caused by lightning transients.

The idea of numerical solution of lightning transients is not new and is more cost effective method of lightning transient analysis than the direct experimental method.

One of the earliest applications of a numerical electromagnetic (EM) analysis to lightning study [1] modeled a lightning channel attached to a tall structure. A time-domain code was used in that study. A similar time-domain code was also used in a study on induced voltages on a distribution line [2] over perfectly conducting ground. A recent study also employs a similar time-domain code [3, 4] to model a lightning channel [5].

However, more authors have applied the Numerical Electromagnetic Code (NEC-2) [6], a frequency-domain code, to lightning electromagnetic pulse (LEMP) studies or lightning-surge analysis [7-14]. Heidler *et al.* [7] used NEC-2 to analyze induced voltages on conductor loops illuminated by LEMP.

Cristina *et al.* [8] employed it to evaluate the EM field inside a building struck by lightning. Chai *et al.* [9] employed this code to study field inside a wire-array lightning protection system for a launch vehicle when it is struck by lightning. The code also has been applied to analyze transient voltages across an insulator of a power transmission tower struck by a direct lightning [9, 10].

Moini *et al*. [10] and Kordi *et al.* [11] applied the time-domain approach utilizing the Thin-Wire Time-Domain code (TWTD) [12], and Baba and Ishii [14, 15] applied the frequency-domain approach utilizing NEC-2 [13-18].

For practical purposes, one of the classes of models applied recently in lightning studies is the so-called electromagnetic models [17]. They are usually based on thin-wire antenna approximation and involve a numerical solution of Maxwell's equations using the method of moments (MoM) [18] to find the current distribution along the lightning channel, from which electromagnetic fields can be computed. This paper presents transient analysis of GSM tower using frequency domain approach, Wire-MoM which is based on thin-wire approximation.

II. METHODOLOGY

A. *Lightning Channel-Base Current Model*

The test waveshapes adopted by various standards for simulating the effects of lightning in the laboratory are 1.2/50μs, 8/20μs, and 10/350μs (in τ_1/τ form; where τ_1 = front time constant, τ = tail time constant) wave shapes.

The time function of lightning current used for numerical analysis purposes also known as the Heidler's model of current source, can be described with the following expression and the waveform is shown in Fig. 1 [19].

$$i(t) = \frac{I_0}{\eta} \cdot \frac{(t/\tau_1)^n}{1 + (t/\tau_1)^n} \cdot e^{-\frac{t}{\tau}} \quad (1)$$

where: I_0 - The peak value of the lightning current

η - The correction factor for the peak value of lightning current peak

n - The factor influencing the rate of rise of the function

τ_1 - Duration of the lightning surge front.

τ - The strike duration; interval between t = 0 and the point on the tail where the function amplitude has fallen to 50 % of its peak value

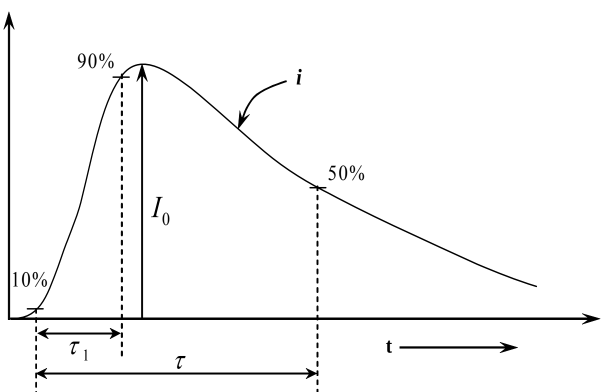


Fig. 1. Waveform of Heidler's model of current source.

B. Numerical Method

In this paper, *Field Theory Approach* [20-23] is adapted for the evaluation of the effects of the lightning over-voltage as this method is more accurate and easier to apply to complex structures consisted of many differently interconnected or oriented conductors. For numerical solution computer program "Wire-MoM" is used which is based on Method of Moments (MoM). Here the computed results are obtained in frequency domain for a current input.

C. FFT and IFFT for Domain Conversion

The method presented in this paper adopts a frequency-domain approach, MoM along with an appropriate Fast Fourier Transform (FFT) algorithm for spectral representation of the lightning channel-base current. By applying an inverse-FFT (IFFT) technique to the derived frequency spectra of required quantities, the time domain result is finally obtained. The FFT and IFFT operations are carried out in MATLAB.

The frequency domain computed result (current or field) for any geometric input data is then multiplied with the Fourier Transform of the input waveform and finally transformed into time domain using IFFT.

The complete flow chart for the time domain analysis of the lightning transients using FFT, IFFT and MoM is shown in Fig. 2.

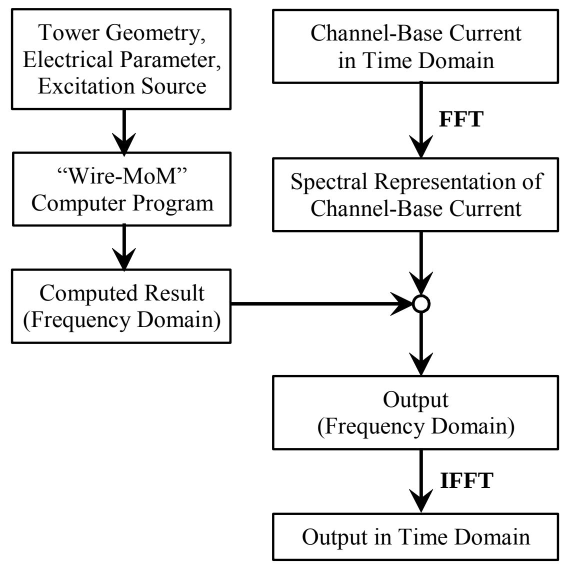


Fig. 2. Time domain transient analysis using Wire-MoM.

D. Modeling Considerations

The lightning channel was represented by a single vertical conductor of 30 m length above the tall tower structure. Lightning channel-base current model used for the simulations throughout this paper is based on the Heidler's model of current source of 10/350 µs wave shape and I_0 = 30 kA, $\eta = \exp(-\tau_1/\tau)$, n = 10, τ = 350 µs, τ_1 = 10 µs unless stated otherwise. For the thin-wire antenna approximation of the tower structure, the tower can be modeled as a complex structure represented by a group of conductors. The segment length is limited by the highest frequency of interest for the frequency domain computation. For numerical computation of the thin-wire approximation of the tower structure, the segment length (ΔL) of the wire must be less than 1/10 of the wavelength of the highest frequency of interest [23-26]. That is,

$$\tfrac{1}{1000}\lambda_{\max} \le (\Delta L) \le \tfrac{1}{10}\lambda_{\max}. \quad (2)$$

To obtain consistent result from the MoM, the radius of the wire should be much less than the segment length (ΔL). Through the analysis performed in this paper, the relation between segment length and radius (a) are kept as follows [24-26].

$$\frac{(\Delta L)}{a} > 120 \cdot \qquad (3)$$

For tower modeling lumped impedance elements were used. Various values of footing resistance such as 40 Ω [7] or higher have been postulated in analyzing lightning current waveforms observed on tall structures. Tower footing resistance of 30 Ω was considered for the simulations carried out. All the simulations were carried out with PEC (Perfect Electric Conductor) ground plane.

III. EMI ANALYSIS OF GSM TOWER

To perform the numerical electromagnetic analysis of a GSM tower struck by a direct lightning stroke, the following simulations are performed by the authors using Wire-MoM. The frequency domain to time domain computation using FFT and IFFT was carried out in MATLAB as mentioned in Fig. 2.

The GSM tower under analysis is considered 42 m high, four legged “Green Field Tower”. The lightning channel was represented by cylindrical elements of segment lengths of approximately 2 m and radius of 1.5 cm and the tower was modeled by cylindrical elements of approximately 2 m segment length and radius of 1 cm. Both the lightning channel and the elevated structure (tower) are considered to be lossless uniform transmission line model having propagation velocity is equal to the velocity of light.

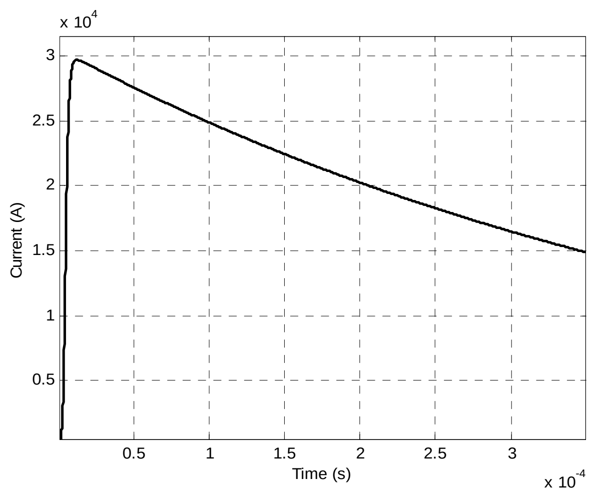


Fig. 3. Waveshape of Heidler’s model of current source.

The lightning channel-base current (Heidler’s model) used for all the simulations is shown in Fig. 3. Here the front time constant (the time required to increase from 10% to 90% of the peak) is 10 μs; and the tail time constant (time interval between t = 0 to point of 50% peak fall) is 350 μs. The time derivative of the channel-base current is shown in Fig. 4. The peak rate of change is 7.63e10 A/s.

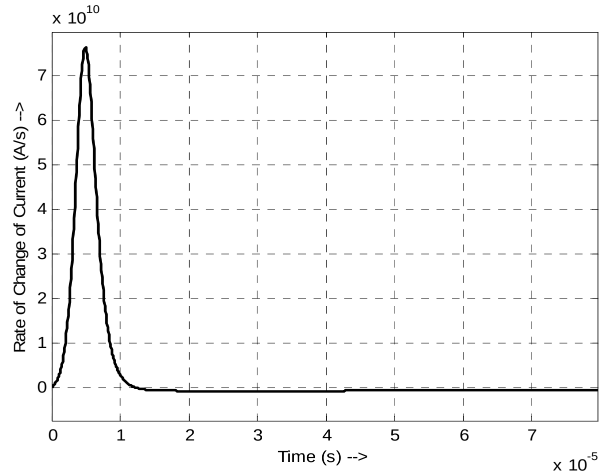


Fig. 4. Rate of change of channel-base current.

A. Current and Surge Response Computation

The model for simulating the current and surge response measurement (by direct method) of the GSM tower is shown in Fig. 5. The current distributions for the complex tower at different heights (for the Leg-A) obtained from the numerical simulations are plotted in Fig. 6 within a 30 microsecond.

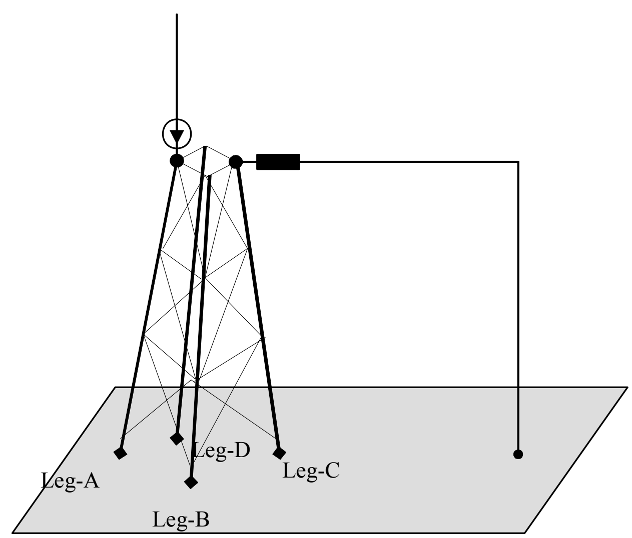


Fig. 5. Computation of current and surge response of 42m high GSM tower.

Fig. 6 shows that the peak current at the top is about 4.7 kA and at the foot of the tower is about 5.5 kA for 30 kA peak channel-base current. These results also agree with the computational results of Rachidi *et al.* [27-29].

In Fig. 7 (magnified plot of Fig. 6), the reflections from the ground are observed in the current waveforms of the GSM tower within 2.5 microsecond window. The reflection time is approximately 0.27 microseconds at the top and 0.22 microseconds at the ½ of the height.

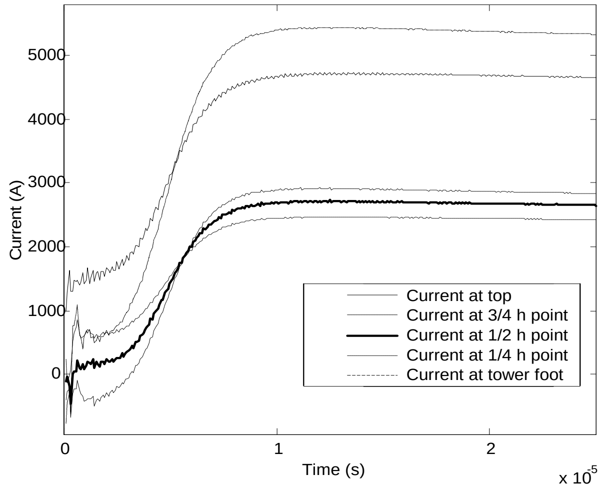


Fig. 6. Current at the leg A of the GSM tower at different heights.

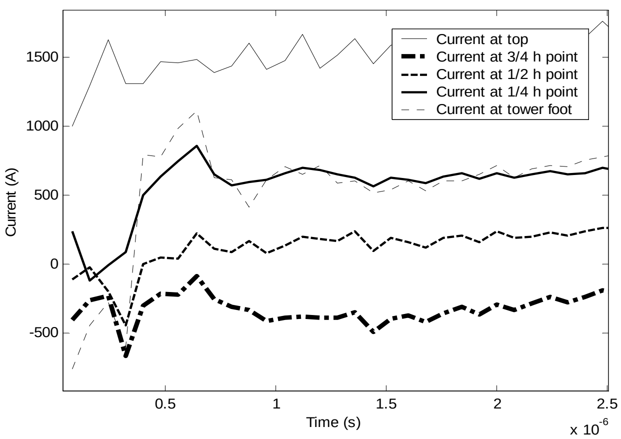


Fig. 7. Reflections of current from the ground and the different parts of the GSM tower.

The surge response of the complex tower was also computed by simulating the surge response measurement by direct method. In this method an auxiliary voltage measuring wire is connected at the top and is extended horizontally over the ground and finally terminated to the ground [9], [10], [14]. The response of the voltage at the top is plotted in Fig. 8. It has an initial transient peak value of 1.4 MV at the top of the tower for the peak channel-base peak current of 30 kA and footing resistance 30 Ω for each of the foot. Then for the positive value of the rate of change of current the voltage is approximately 300 kV and crosses the zero line at 5μs. The voltage is negative for the negative rate of change of channel-base current.

As it can be seen from Fig. 8, the surge response is characterized by a faster rise time and a shorter duration with respect to the channel-base current. And as the peak value of the voltage is up to few hundreds of kV (300kV), therefore can cause flashover [30]. There are lots of fluctuations in the response, which may be caused by the mismatch of the tower and the ground resistivity and the reflections from the different interconnected arms of the tower.

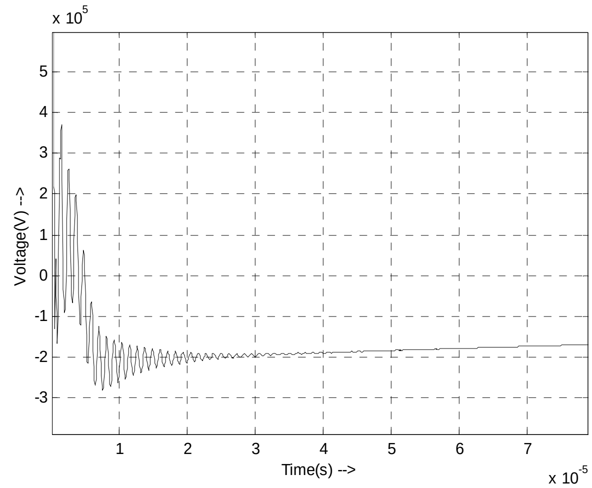


Fig. 8. Voltage at the top of the GSM tower computed by simulating the direct method.

B. *Induced Current and Voltage on a Mounted Dipole*

In this simulation, the induced current and voltage on a dipole antenna mounted vertically and horizontally was computed. The model simulating the induced current distribution and voltage on a mounted dipole antenna is shown in Fig. 9.

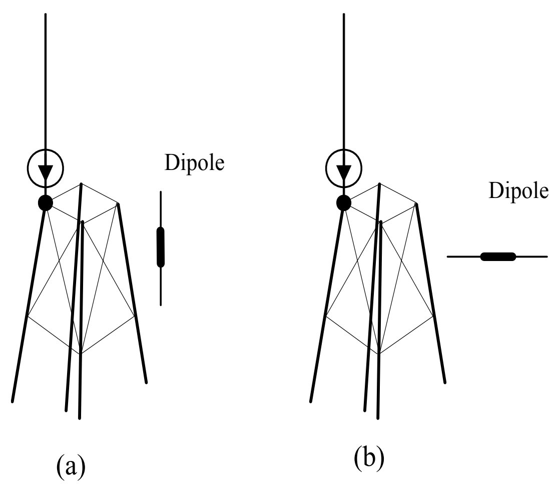
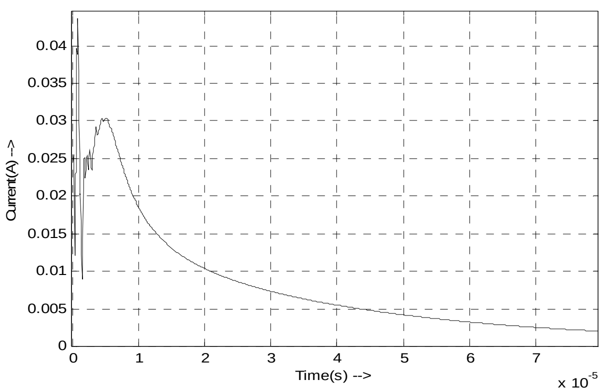


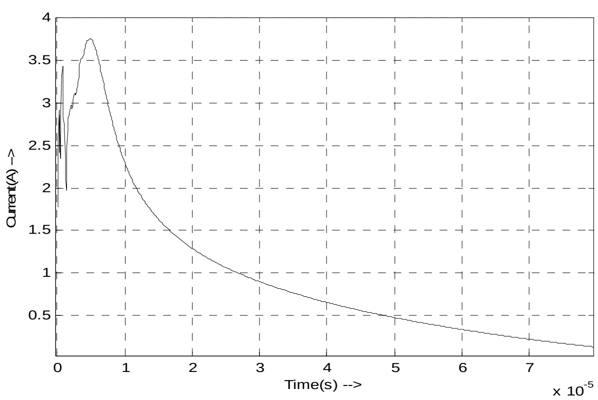
Fig. 9. Induced current and voltage computation for (a) Vertically mounted, and (b) Horizontally mounted dipole.

The current distribution and the induced voltage at the feed point of the dipole was computed both for horizontal and vertical mounting. The characteristic impedance of the dipole was 50 Ω, length of the dipole is 0.75 m, and radius of the wire is 1mm.

The induced current on the dipole in time domain are shown in Fig. 10. From the induced current waveforms, we see that larger amount of current and voltages are induced while the dipole is mounted vertically rather than horizontally. The induced peak current and voltage for vertical mounting is several amperes (3.75A) and several hundred volts (188 V). For horizontally mounted dipole, the peak current induced is several mA (30 mA) and the induced peak voltage is of several volts (1.52V). And the induced voltage is characterized by a faster rise time and a shorter duration with respect to the channel-base current.



(a)



(b)

Fig. 10. Induced current on the dipole antenna: (a) Horizontally mounted, and (b) Vertically mounted.

C. Field Computation at Different Points

The model simulating the field computed at different distances from the tower is shown in Fig. 11.

For the model shown in Fig. 11, *x*, *y* and *z* components of the electric and magnetic field intensities of the electromagnetic pulses radiated by the tower undergoing direct lightning strike was computed in time domain up to 500 m from the tower foot. Near field points were y = 5m; z = 40 m; x = 10 m, 30 m, 50 m … 470 m, 490 m.

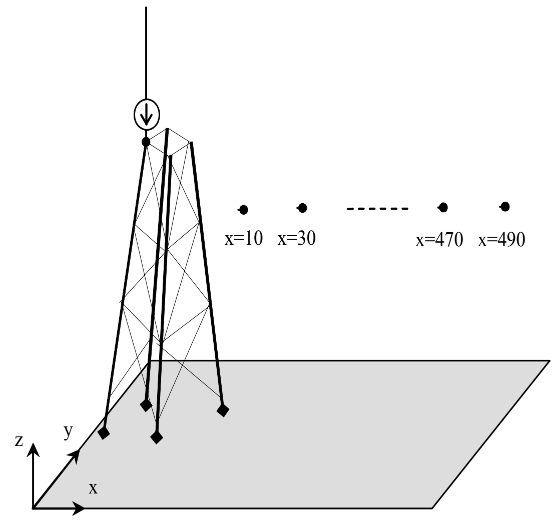


Fig. 11. Near field points for field computation.

From the simulation results it is obtained that the vertical component of the electric field, Ez and the horizontal component of the magnetic field, Hy are the most dominating. The time dependent characteristics of the Ez and Hy are plotted in Figs. 12 and 13. From the figures it can be seen that for the vertical electric field, there is a slower initial peak and a faster decay. But for the magnetic field, the initial peak is sharper and the decay is slower than that of the electric field. Similar results have been presented by Diendorfer who extended the Diendorfer and Uman (DU) model [31] to take into account the presence of an elevated strike object, and while the strike objects considered in his study were not taller than 20 m, and further investigated by Baba *et al.* (Figs. 3 (a) and 4 (a) of [32]).

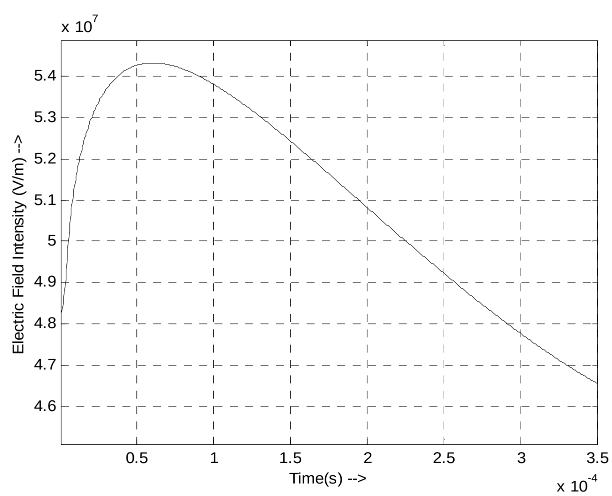


Fig. 12. E_z at the point (10 m, 5 m, 40 m) near the GSM tower.

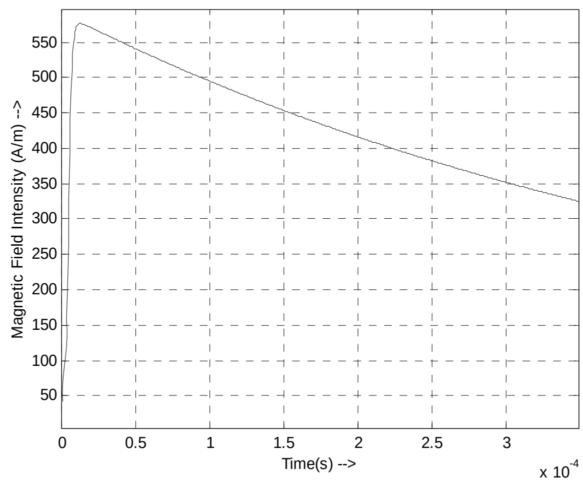


Fig. 13. Hy at the point (10 m, 5 m, 40 m) near the GSM tower.

The peak values of the electric and the magnetic field intensities from the simulation are provided in tabular forms in tables 1 and 2, respectively at different near field points.

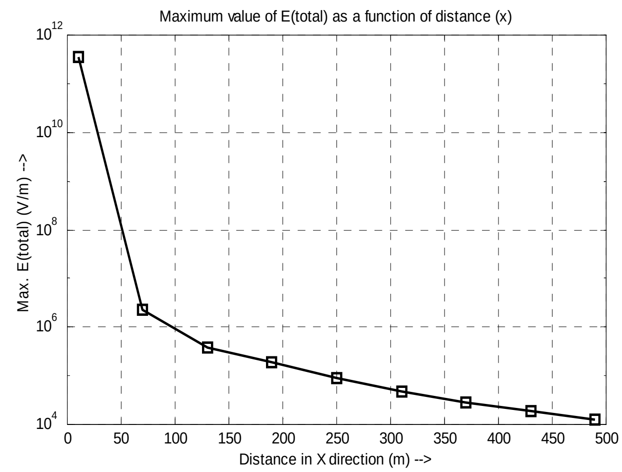
Table 1. Peak electric field intensities at different near field points.

x (m)	E_x (V/m)	E_y (V/m)	E_z (V/m)	E_{total} (V/m)
10	3.4881e7	1.0987e7	5.4321e7	3.4881e11
70	1.7432e6	7.3191e4	1.3883e6	2.033e7
130	3.4437e6	7.2219e3	3.9457e5	4.782e5
190	1.0059e5	1.4247e3	1.6252e5	1.7416e5
250	3.8013e4	415.9924	8.0323e4	8.0828e4
310	1.7149e4	157.7499	4.5004e4	4.424e4
370	8.7793e3	72.3284	2.763e4	2.674e4
430	4.9357e3	38.3323	1.8175e4	1.74e4
490	2.9814e3	22.736	1.2614e4	1.2085e4

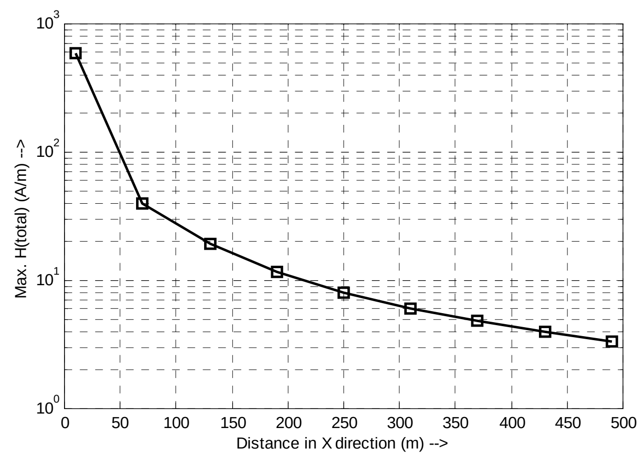
Table 2. Peak magnetic field intensities at different near field points.

x (m)	H_x (A/m)	H_y(A/m)	H_z (A/m)	H_{total} (A/m)
10	72.6485	579.778	94.6636	591.9303
70	0.2646	40.0539	1.3174	40.0764
130	0.1252	19.1144	0.3572	19.1181
190	0.0609	11.649	0.1591	11.6502
250	0.0343	8.0713	0.0893	8.0719
310	0.0216	6.0606	0.0571	6.0609
370	0.0147	4.8028	0.0397	4.8030
430	0.0106	3.9538	0.0292	3.9539
490	8.0324e-3	3.3476	0.0224	3.3477

The peak values of field intensities as a function of distance from the tower are shown in Fig. 14. They demonstrated that the peak electric and magnetic field intensity decreases exponentially with the increase in distance from the lightning channel regardless of ground conductivities [33].



(a)



(b)

Fig. 14. Peak value of (a) $E_{(total)}$ (V/m) (b) $H_{(total)}$ (A/m) at different near field points along x-axis.

CONCLUSION

The experimental evaluation for the lightning transient study is much expensive than the numerical solutions. The authors of this paper carried out the numerical electromagnetic analysis of a GSM tower undergoing a direct lightning strike for the lightning transient study. As the MoM automatically computes the electromagnetic coupling between the conductors so no coupling model was required and the solution by MoM is more accurate than the time domain electromagnetic transient program (EMTP) solution [16], [17], [26].

The analysis shows that the amount of current and voltage induced on the dipole elements are also of large magnitude enough for the degradation and disruption of the transmission information. The result and analysis also provides that a large amount of current and voltage (few hundreds of kV) is generated by the lightning over-voltage which can cause flash over and implies the installation of surge arrester or lightning current arrester for the protection of the base station.

The results of current and its associated fields at near to the lightning source are observed to be agreed well with other numerical results. In this analysis the ground plane was considered to be perfectly conductive; so, the effect of finite ground conductivity is out of the scope of this analysis.

ACKNOWLEDGMENT

The authors wish to thank the Committee for Advanced Studies and Research (CASR) of Khulna University of Engineering and Technology (KUET) for providing financial and logistic support in this research work.

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