Analysis of Lightning Surge Characteristics on Transmission Tower

M. S. Yusuf, M. Ahmad, M. A. Rashid, *Member IAENG*, and M. O. Goni

Abstract— **Lightning performance of transmission lines is an important factor for the electric utility companies. Now a day, this matter is getting more priority with the increasing requirement for power quality. In order to understand the lighting surge phenomena clearly, the author used a reduced scale model of tower for the analysis. But in real life, the actual tower is subjected to the lightning. It is then necessary to analyze the characteristics of actual tower when subjected to lighting as in case of reduced scale model tower. So, the authors also simulate an actual tower to obtain the surge characteristics phenomena. In this case, the three-phase conductors and the earth wire have been considered for the analysis. The apparent characteristics of a tower may be influenced by the presence of an earth wire. However, this issue has been paid a little attention in the modeling of a tower for the well-known Numerical Electromagnetic Code (NEC-2) simulations. In this paper, firstly, a reduced scale model is analyzed in different aspect, and then the surge characteristics of an earth-wired tower as well as phase conductors of the tower struck by lightning are studied with the help of NEC-2 in case of direct and indirect stroke.**

Index Terms— **Earth wire, Phase conductors, Surge impedance, Transmission tower, NEC-2**

I. Introduction

Transmission line faults caused by lightning strikes give serious damages, such as a massive blackout and instant voltage drop, on electric power systems. Therefore, the rational lightning protection measures should be adopted for ensuring a stable electric power system. Analysis of lightning surges is important for power systems, since lightning strokes on transmission towers, shield wires and phase conductors may cause insulation flashover which may lead interruption of continuous power transmission. When a lightning strike occurs on a tower or on a shield wire near potential on the phase conductor, which is the sum of nominal system operating voltage and induced potential due to lightning. For calculation of the potential across the insulator strings, the surges both on the tower and induced voltages on the phase conductors need to be determined.

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Several studies on surge analysis of the transmission lines have been carried out to evaluate the effect of the lightning protection measures and to estimate the lightning outrage rates [1]-[3] There are many works that have been devoted to the analysis of lightning surges on transmission towers. Experimental studies on this subject have usually been carried out in Japan [4] and measured results have become an important base for computer simulations. In the experimental work done by Kawai surge response of transmission tower has been measured [1]. Later Ishii performed experiments on a full scale tower with phase conductors and ground wires [2, 3] and as a result of these experiments a multistory tower model has been proposed for multiconductor analysis in EMTP. Series of experiments later have been continued on a different tower configuration [4] to generalize the results obtained in previous works. On the other hand, in the area of numerical developments, Almeida and Correia De Barros [5] used finite element method for the EMTP simulation. Later Ishii and Baba [6] analyzed a large scale UHV transmission tower using moment method by solving electric field equations directly, and in their study the effect of slant elements, horizontal elements and crossarm has been investigated. Using the same method, they also investigated lightning surge characteristics of a transmission line comprising a tower, a shield wire and phase conductors [7]. Next, tower body and crossarms are modeled in details using short lines sections [8]. Mozumi et al. analyzed archorn voltages of a simulated 500 kV twin-circuit line [9]. In this paper, lightning surges on a transmission tower are analyzed using the numerical solution of the electric field integral equations used in NEC-2 are first obtained. The measuring method of tower surge impedance are briefly explained and then this effects of the measuring methods and the arrangements of the measuring wires on the evaluated tower surge impedance are studied by the NEC-2. Lightning surge phenomena are analysis are given in [10]. Overhead transmission line modeling for over voltage calculation is explained by Juan A. Martínez et al. in [11]. Mohd Z. A. Ab Kadir et al. analyzed back flashover, shielding failure and determination of arrestor in details energy [12]. P. Yutthagowith et al. proposes the application of a partial element equivalent circuit method to lightning surge analyses in [13]. In [14], Y. Du, X. Wang and M. Chen, explained the transient surge response of a vertical conductor over the ground. In analyzing the lightning performance of overhead power transmission lines and substations, the lighting surge characterstics of transmission line components as well as the statistical data of lightning such as the ground flash density and the strock peak current distributions are essensial. Among the transmission line components, tower surge characterstics including the tower footing impedence charactersticsin the linear region are

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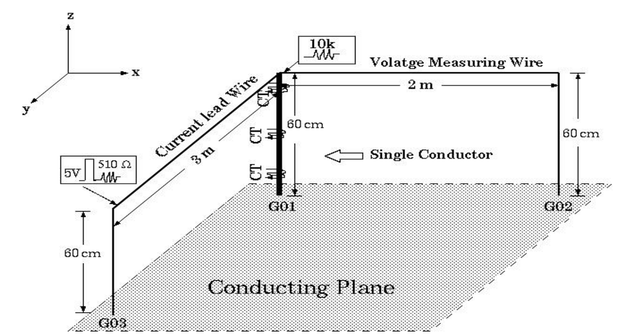


Fig. 1. Arrangement of the vertical conductor system for the simulation with NEC-2 with ground plane.

probably the most fundamental factors since they contribute directly to the insulator voltages during a lightning hit. Particularly for such tall structure as EHV or UHV double-circuit towers, the characterstics become more dominant owing to the longer round-trip time of a travelling wave in the tower. An agreement on the interpretation of this phenomenon,however,has not been reached yet.

For the present analysis, the (NEC-2) is employed. It is a widely used three-dimensional (3-D) electromagnetic modeling code based on the MoM in the frequency domain, and is particularly effective in analyzing the electromagnetic response of antennas or of other metallic structures composed of thin wires. A vertical conductor system needs to be decomposed into thin wire elements, and the position, orientation and the radius of each element constitute the input data, along with the description of the source and frequency to be analyzed. In the analysis, all the elements in the systems are treated as perfect conductors. To solve the time varying electromagnetic response, Fourier transform and inverse Fourier transform are used. Firstly, reduced scale model of tower has been taken into account for details analysis of lightning surge phenomena clearly. Then the study in this paper precedes the work done to obtain, the surge characteristics of an earth-wired tower as well as phase conductors of the tower struck by lightning are studied with the help of NEC-2 in case of direct and indirect stroke.

Rest of the paper is organized with the theoretical formula of surge impedance in section II. Applications of NEC-2 to the analysis of reduced scale model of vertical conductor surge response are described in section III. Then the numerical electromagnetic analysis of earthed wire tower strucked by lightning analyzed in section IV. Estimation of surge impedance of various double-circuit transmission towers are given in section V. Finally, Conclusion is given in Section VI.

II. THEORETICAL FORMULA OF SURGE IMPEDANCE

There is a theoretical formula of surge impedance [15] of a vertical conductor, in case with ground plane and without ground plane. Suppose that lightning surge strike on the vertical conductor whose height is h and radius is r. Then the surge current wave is reflected at the ground of the perfect conductor and returns to the top of the vertical conductor. Introducing the current reflectivity $\beta = 1$ and the magnetic field reflectivity $\gamma(\gamma_i, \gamma_r) = 0$, the theoretical formula of surge impedance which is very close to the well-known empirical formula of Dr. Hara,

$$Z = 60\left\{ln\left(\frac{2\sqrt{2}\,h}{r}\right) - 2\right\} \quad (1)$$

is obtained as follows:

$$Z = 60\left\{ln\left(\frac{h}{2r}\right) - \frac{1}{4}\right\} = 60\left\{ln\left(\frac{2\sqrt{2}\,h}{r}\right) - 1.983\right\} \quad (2)$$

The above expression gives the surge impedance of the vertical conductor just after the occurrence of the reflection of the traveling wave propagation down from the top of the structure. However if it is considered that $\beta = \gamma_i = \gamma_r = 1$, the potential $V(t)$generated in the vertical conductor at $h$became,

$$V(t) = \frac{c\mu_0 I_0}{2\pi}\left\{ln\frac{(ct+2r)}{2r} - \frac{ct}{2(ct+r)}\right\}$$

The above equation can be modified by substituting $ct = 2h$, where c is the velocity of light and assuming $h \gg r$ as follows:

$$Z = 60\left\{ln\left(\frac{h}{r}\right) - \frac{1}{2}\right\} = 60\left\{ln\left(\frac{2\sqrt{2}\,h}{r}\right) - 1.540\right\} \quad (3)$$

On the other hand, if there is no ground, the following formula is induced

$$V(t) = \int_0^{ct} (-E_i.dl) = \frac{c\mu_0 I_0}{2\pi}\left\{ln\frac{(ct+2r)}{2r} - \frac{ct}{2(ct+r)}\right\}$$

Substituting $ct = 2h$ and assuming $h \gg r$in the above equation, we get

$$Z = 60\left\{ln\left(\frac{h}{r}\right) - \frac{1}{2}\right\} = 60\left\{ln\left(\frac{2\sqrt{2}\,h}{r}\right) - 1.540\right\} \quad (4)$$

This formula given by equation (4) is the same as equation (3). Then we calculate the value of surge impedance by these equations and compare with NEC-2 results comparing with and without ground plane.

III. APPLICATION OF NEC-2 TO THE ANALYSIS OF REDUCED SCALE VERTICAL CONDUCTOR SURGE RESPONSE

The analysis of transient behavior of tower struck by lightning is an important problem when studying the lightning performance of transmission lines. The issue has gained more importance with the recent use of instrumented telecommunication towers to capture lightning return stroke currents, also in power system equipment (circuit breakers, disconnects, control and protection circuits), and in household appliances has increases the interest of transients. From this point of view, transient caused by lightning (direct and or indirect) can be one of the major causes of malfunction, or even destruction of electrical equipment's. Direct lightning may be defined as a lightning stroke which directly hits a line connected to the installation or the equipment .On the other hand, Indirect, if the strike is at a certain distance and the currents are induced by the electromagnetic field generated by the lightning discharge. In this research, if the lightning current channel does not terminate then it has been denoted as without ground plane and vice-versa. This section describes the numerical simulation of the surge response of a vertical conductor, including the effects of ground plane and without ground plane [16]-[19].NEC-2 is applied to the electromagnetic field analysis of vertical conductor surge response.

For the analysis different reduced scale model of vertical conductor were taken such as 60 cm, 90 cm and 120 cm long. Fig.1. shows reduce-scale of 60 cm model of the single

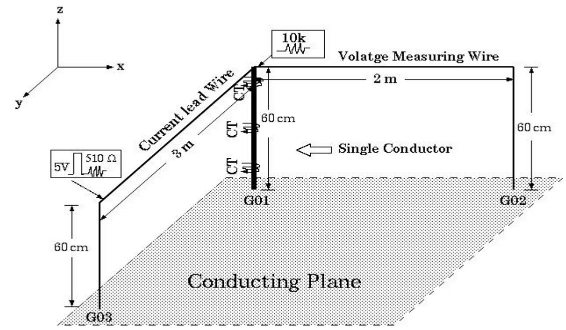


Fig. 1. Arrangement of the vertical conductor system for the simulation with NEC-2 with ground plane.

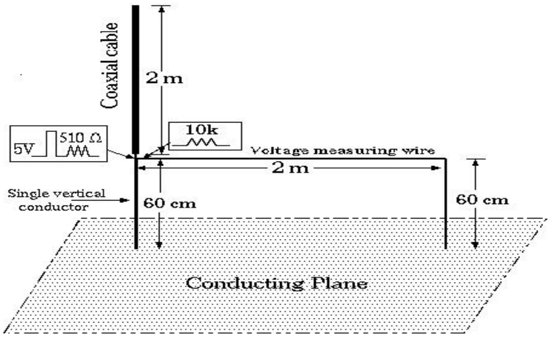


Fig. 2. Arrangement of the vertical conductor system for the simulation with NEC-2 without ground plane.

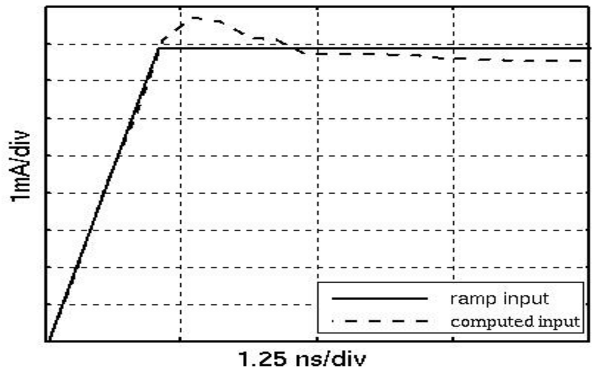


Fig. 3. Waveform of the injected current used for simulation.

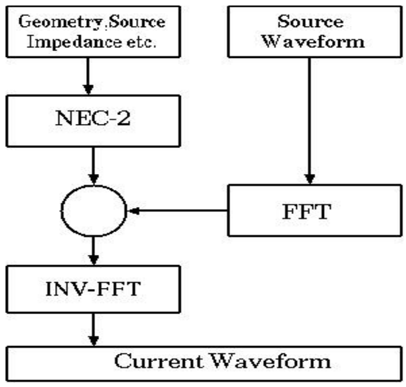


Fig. 4. Flowchart of the solution using NEC-2.

vertical conductor system for the surge analysis. The arrangement of the current lead wire connected to the top of the vertical conductor with the existence of ground plane and without ground plane is indicated in Fig.1 and Fig.2 respectively. Whereas Fig.1 simulates a lightning stroke to mid-span and also have been called the refraction method. Fig.2. also illustrates an arrangement for analysis, which simulates a vertical lightning stroke hitting a tower top. In this analysis, two kinds of lightning strokes are simulated: one is a return stroke and the other is a downward traveling current wave.

In the case of a return stroke to a tower, a downward leader, which is similar to a charged vertical transmission line whose lower end is open, contacts the top of the tower. This situation can be simulated by placing a pulse current generator at the tower top. Another type of the lightning phenomena caused by a downward traveling current wave can also be examined. In such kinds of strokes, a current wave is thought to propagate down the lightning channel from the cloud to the tower top. For the simulation of this situation, a pulse current generator needs to be placed remotely above the channel. However, the computed waveforms for this case of current injection, a current wave traveling down the current lead wire, are similar to those of return stroke type without the influence of the finite length of the wire.

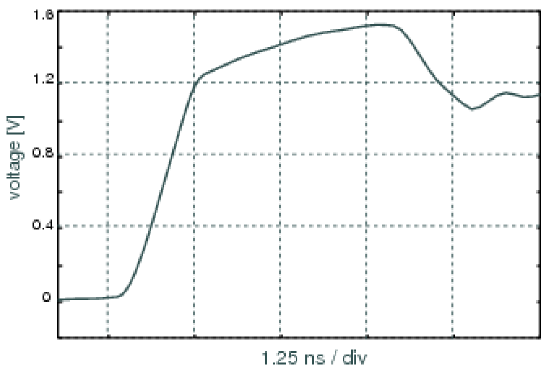
A voltage measuring wire of 200 cm in length is placed perpendicular to the current lead wire and is connected to the top of the vertical conductor, which is 60 cm in height, and radius of 0.05 cm. The ends of the horizontal voltage measuring wire in both cases are stretched down and connected to the ground through matching resistance. If the electromagnetic wave inside the vertical conductor system travels at the velocity of light, this termination condition does not affect the phenomena at the vertical conductor within 13.33 ns. A step current pulse generator having pulse voltage of 5 V in magnitude, rise-time of 1 ns and pulse width of 40 ns is installed in both cases which is meant to incorporate the influence of the induction from the lightning channel hitting the vertical conductor. Fig.3. shows the waveforms of the injected current for the simulation using NEC-2.Since NEC-2 is a computer code in the frequency domain, the Fourier transform and the inverse Fourier transform are used to solve the time-varying electromagnetic fields.

The flowchart of the NEC-2 simulation is shown in Fig.4. For the numerical analysis, the conductor system needs to be modeled with segments according to the modeling guidelines stated in the preceding section. To save the computation time, the conductors of the system are divided into 10 cm segments in this research. This segmentation must satisfy electrical consideration relative to the wavelength as:

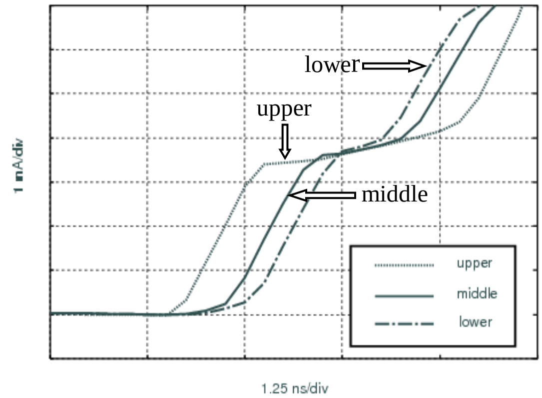
$$10^{-3}\lambda \leq \Delta L \leq 0.1\lambda$$

This requirement is too severe to be satisfied exactly, since wider frequency range is needed to investigate the transient characteristics of such a system [20].

To evaluate the voltage of the top of a structure, $10\,k\Omega$ resistance was inserted between the top of the structure and the end of the voltage measuring wire. The voltage at the top of vertical conductor through the horizontal voltage measuring wire is obtained and also the waveform of current flowing through the vertical conductor is obtained from the simulation. The system of structures under the analyses was postulated to be on the perfectly conducting groundof cupper with conductivity 5.8×10^{7} ohm/meter. Then we calculate the surge impedance, which is defined by the ratio of the instantaneous values of the voltage to the current at the moment of voltage peak. As the pulse applied to the

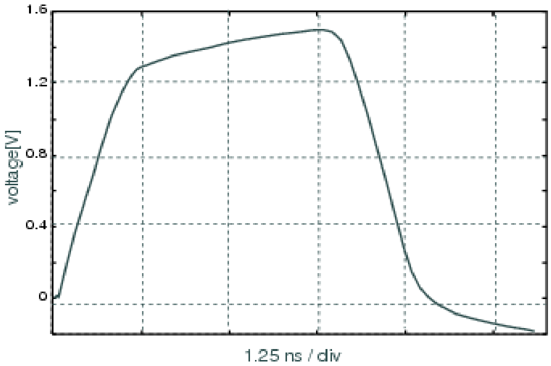


(a) Computed voltage waveform.

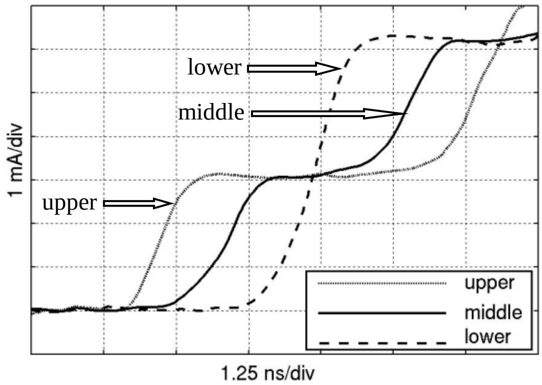


(b) Computed current waveform.

Fig.5. NEC-2 results of voltage at the top and currents through the vertical conductor of 60 cm in case with ground plane.



(a) Computed voltage waveform.



(b) Computed current waveform.

Fig. 6. NEC-2 results of voltage at the top and currents through the vertical conductor of 60 cm in case without ground plane.

current lead wire according to Fig.5, the current starts flowing through the vertical conductor instantly. However, for the arrangement as shown in Fig. 1, the current through the vertical conductor is delayed by the round-trip time of the travelling wave in the conductor. While in both cases, the reflection wave from the ground reaches the top of the vertical conductor at $t = 2h/c$, where h is the height of the vertical conductor and c is the velocity of light. That's why the maximum potential of the vertical conductor will occur at time $t = 2h/c$.

A. Surge Simulation by NEC-2 in case of With Ground Plane

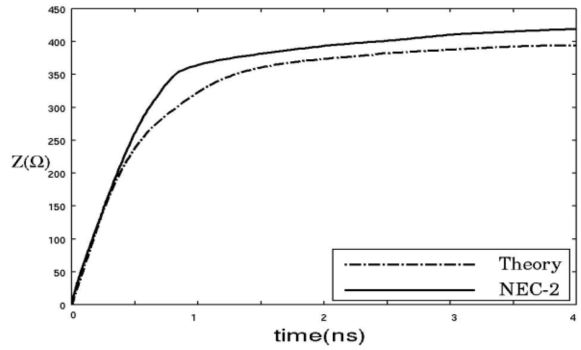
Considering the Fig.1, we want to find the voltages and currents with the simulation by the NEC-2. Fig. 5 shows the simulation results by the NEC-2 of the voltage at the tower top and current through the vertical conductor in case with ground plane. As soon as the reflected wave from the ground reaches the top of the conductor, the potential waveforms decrease, which is observed after t= $2h/c$ = 4 ns exactly that means the traveling wave is propagating at the velocity of light. The simulation result of voltage waveforms at the tower top obtained is shown in Fig. 5 (a). The computed waveforms of current flowing through the vertical conductor are obtained at the location marked 'CT' in Fig.1. The current sensors are placed about 20 cm apart in the vertical conductor to obtain the lower, middle and upper currents. These simulation results of currents waveform obtained are given in Fig. 5(b). The influence of ground plane can be observed in Fig. 5(b), where the field produced by the current injected horizontally induces current of small magnitude before the actual surge current flowing through the vertical conductor. The simulation results are in well agreement with the FDTD results [21].

B. Surge Simulation by NEC-2 in case of Without Ground Plane

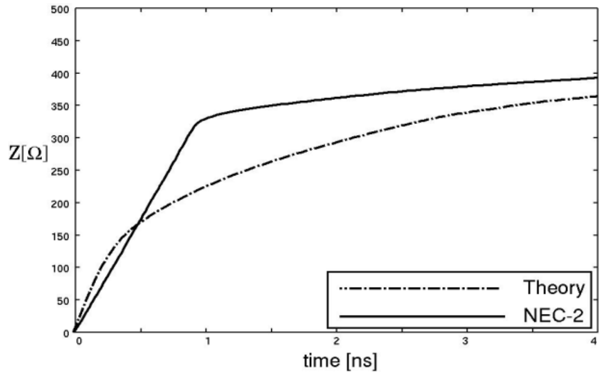
Fig.6 shows the results of the voltage across the voltage measuring wire and currents through upper, middle and lower end of the vertical conductor respectively in the absence of ground plane. However, in this case of analysis, the waveforms of current through the vertical conductor are somewhat different from Fig. 5(b). The major difference can be noticed at the starting zone of the lower end current and then current after rising to its peak. The surge currents through the vertical conductor after 1 ns of rise-time are almost flat and there is no such contributions of small induce current like Fig. 5(b), because of absence of ground plane for injected current. Also, the current starts flowing instantly through the vertical conductor without being delayed. The voltage waveforms reach their peaks at 4 ns after the beginning, which indicates that a traveling wave propagates along the conductor with the velocity of light.

C. Surge Impedance's

We define the surge impedance by the ratio of the instantaneous values of the voltage at the tower top or vertical conductor to the current flowing through it at the moment of voltage peak. The theoretical values of surge impedance with ground plane derived by Takahashi are just after the surge electric current reaches the ground and produced reflected current wave. There is another empirical formula of surge impedance (1), which is very close to (2). Here we plotted the empirical values of surge impedance considering the effect of ground plane and without ground plane along with the simulation at $0 \langle t \langle 2h/c$ which is shown in Fig.7. Also we need to know surge impedance at $t = \frac{2h}{c} = 4\,ns$. Computed values are obtained by NEC-2 are

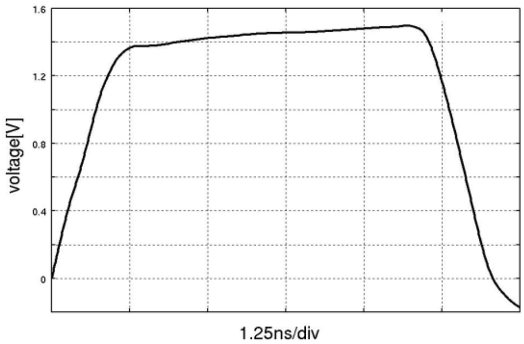


(a) Without ground plane

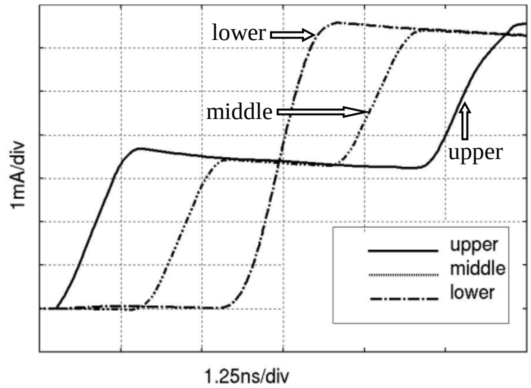


(b) With ground plane

Fig. 7. Surge impedance of the vertical conductor of 60 cm at $0 < t \leq 2h/c$.



(a) Computed voltage waveform.

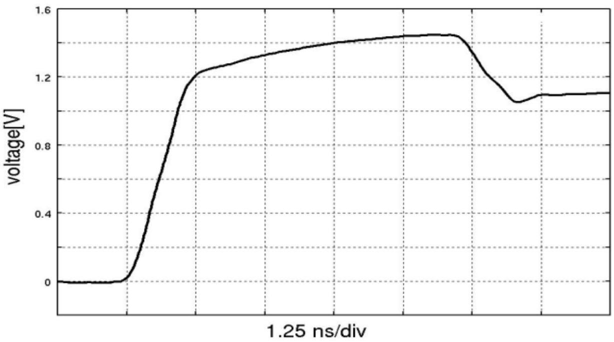


(b) Computed current waveform.

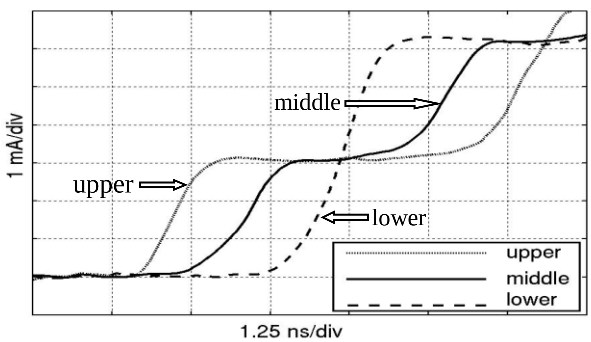
Fig. 8. NEC-2 results of voltage at the top and currents through the vertical conductor of 90 cm in case without ground plane.

approaching closely at $t \approx \frac{2h}{c}$. For comparison similar to the 60 cmof height model, 90 cm and 120 cm height model was analyzed by the same procedure as described in the preceding sections. The input was same in all these cases as shown in Fig.3, in which the rise time was 1 ns. The voltage, current and impedance waveforms were obtained in these cases are shown in the following Figs. 8, 9 and 10 respectively. In case of 90 cm model the current wave which is reflected from the ground reaches at the top after about 6 ns which shows that the electromagnetic wave propagates through the conductor with the velocity of light. On the other hand, for 120 cm model the reflection occurs after 8 ns, which also shows that the propagation velocity is the velocity of light.

From the voltage and current the impedence curve is plotted as shown in Fig.10. It is seen that value of surge impedence without ground plane case is more than with ground plane cases which was also in case of 60 cm model. The theoritical value of surge impedence can be explained by the theoritical value of Takahashi formula,which is considered without ground plane case and empirical formula of Hara et al. is considered with ground plane case. Similar to the 90 cm model, in case of 120 cm model we see that in both the cases the voltage waveform reaches their peak value after about 8 ns and then decreases. In case of the current wave, the reflection arrives after 8 ns, which shows that in this case electromagnetic wave also propagates with the velocity of light. The value of surge impedance without ground plane case is more than in case of with ground plane as explained in 60 cm model. It is also seen that the value of surge impedance increases with the time as long as it reaches to the surge impedance value of the vertical conductor and then decreases.



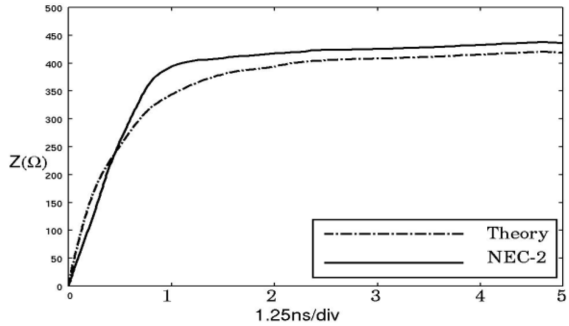
(a) Computed voltage waveform.



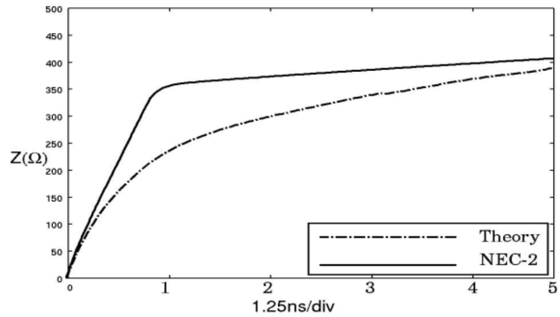
(b) Computed current waveform.

Fig. 9. NEC-2 results of voltage at the top and currents through the vertical conductor of 90 cm in case with ground plane.

Similar to the 90 cm model, in case of 120 cm model we see as shown in Figs. 11 and 12 that in both the cases the voltage waveform reaches their peak value after about 8 ns and then decreases. In case of the current wave,the reflection arrives after 8 ns, which shows that in this case electromagnetic wave also propagates with the velocity of

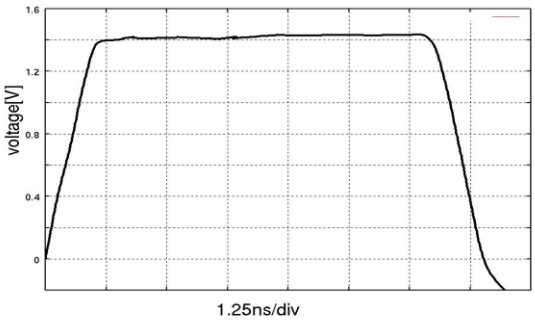


(a) Without ground plane

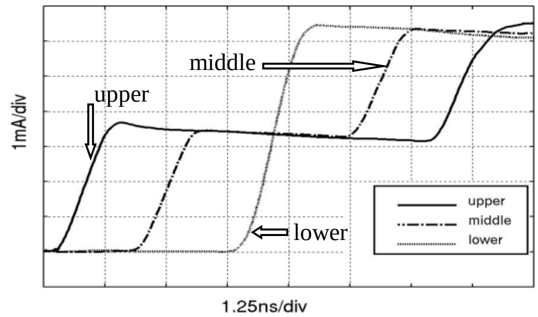


(b) With ground plane

Fig. 10. Surge impedance of the vertical conductor of 90 cm at $0 < t \leq 2h/c$.

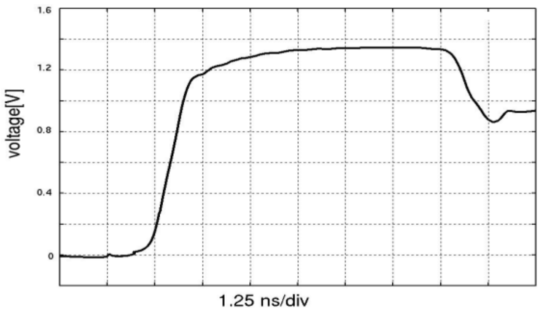


(a) Computed Voltage waveform

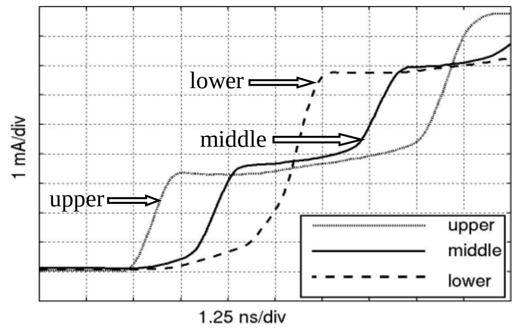


(b) Computed current waveform.

Fig.11. NEC-2 results of voltage at the top and currents through the vertical conductor of 120 cm in case without ground plane.



(a) Computed voltage waveform



(b) Computed current waveform.

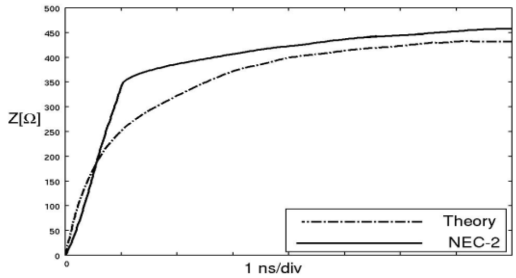
Fig. 12. NEC-2 results of voltage at the top and currents through the vertical conductor of 120 cm in case with ground plane.

light. The value of surge impedence without ground plane case is more than in case with ground plane as explained in 60 cm model. It is seen from Fig.13 that the surge impedence increases with the time as long as it reaches to the surge impedence value of the vertical conductor and then decreases.

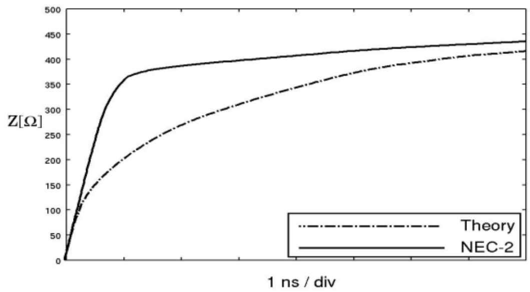
D. Influence of the Method of Current Injection

For the analysis of current injection at the different point is numerically simulated. In this case a pulse generator is inserted into the current lead wire at different places from the top of the vertical conductor in the current lead wire as shown in Fig. 14. The pulse generator are placed as case (i) at 150 cm above, case (ii) at 100 cm above and caseand (iii) also on the top of the vertical conductor. These three arrangements of pulse generator are simulated with the help of numerical electromagnetic code (NEC-2). The computed waveforms of the conductor top voltages and currents flowing into the conductor are shown in Fig. 15. The broken line, solid line and dotted lines result corresponds to case (i), case (ii) and case (iii) respectively. The voltage waveform for case (iii) reaches its peak value at $t \approx 2h/c$ = 4 ns which shows that the propagation velocity is same as light. On the other hand for other two cases there is a time delay of 3.4 ns in case (ii) and 5 ns in case (i), which also shows that the electromagnetic wave is propagating through the conductor with the velocity of light. For the current waveforms it is observed that only in case (iii) the reflection from the perfectly conducting ground occurs after 4 ns. But in other two cases there are time delays for reflection due to time required to flow electromagnetic wave through the vertical conductor.

The difference of the surge impedance's depends on the arrangement in the measurement can be explained by the electric field associated with the steep-front currents flowing in the current lead wire, the voltage measuring wire or earth wire and the vertical conductor or tower. With vertically applied input or without ground plane case, the positive surge current from the pulse generator flowing into the vertical conductor and the negative current propagating up the vertical current lead wire produce the strong upward electric field. This makes the injected current split more into the voltage measuring wire and less into the vertical conductor than in the case of Fig. 5(b), resulting in higher vertical conductor surge impedance's. On the other hand, a strong horizontal electric field is produced by the negative current into the horizontal current lead wire.



(a) Without ground plane



(b) With ground plane

Fig. 13. Surge impedance of the vertical conductor of 120 cm at $0 < t \leq 2h/c$.

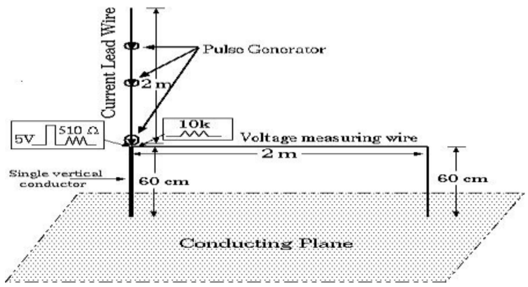
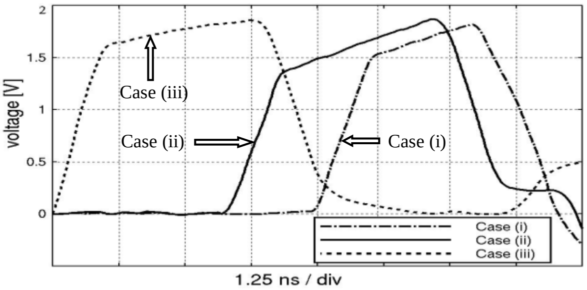
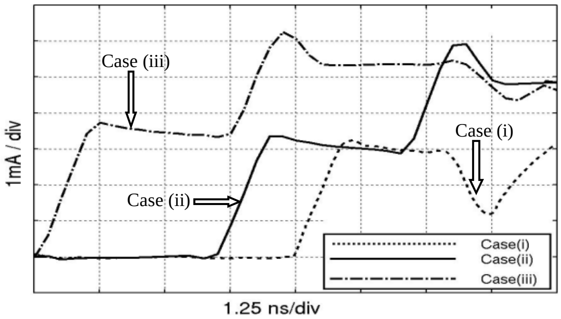


Fig. 14. Arrangement for the analysis by the direct method, where a pulse generator is placed at different position in the current lead wire.



(a) Voltage waveform



(b) Current waveform

Fig. 15. Computed waveforms of voltage and currents for injection at different height of the current lead wire.

TABLE I
Surge impedance comparison table

Tower height	Arrangements	Theory	NEC-2
60	Without ground plane	395	425
	With ground plane (Ω)	368	395
	Effect of ground plane in %	6.8	7
90	Without ground plane (Ω)	415	440
	With ground plane (Ω)	420	390
	Effect of ground plane in %	6.4	8.6
120	Without ground plane (Ω)	435	460
	With ground plane (Ω)	436	415
	Effect of ground plane in %	6	9.7

This makes the injected current split more into the vertical conductor and less into the voltage measuring wire than in the case of Figs. 4(b) that results in lower surge impedance's as shown in Fig. 5 also demonstrates in Table I. It was also observed for 90 cm and 120 cm models, which has been shown in different Figs. 8 to 15. It must be noticeable that as the height of the vertical conductor with same radius was increasing the value of surge impedance was increasing as it is found according to the theoretical without ground plane and 7.35% in case of with ground plane. The maximum effect of ground plane is to be less than 10% with the simulation and theoretical investigation [22]-[25].

IV. NUMERICAL ELECTROMAGNETIC ANALYSIS OF EARTH -WIRED TOWER STRUCK BY LIGHTNING

In this type of simulation, two kinds of lightning stroke as indicated in the previous research are simulated: one is a return stroke and other is a downward traveling current waveform as shown in Fig. 16. In the case of a return stroke to a tower, a downward leader, which is similar to a charged vertical transmission line whose lower end is open, contacts the top of the tower. This situation can be simulated by placing a pulse current generator at the tower top, except for an actually slower velocity of return current wave than the velocity of light. For reduced scale model which employed a spiral wire or a straight wire suspended vertically above the tower, showed that the speed of upward moving current

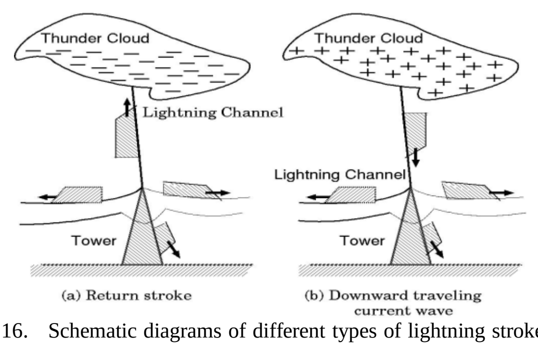
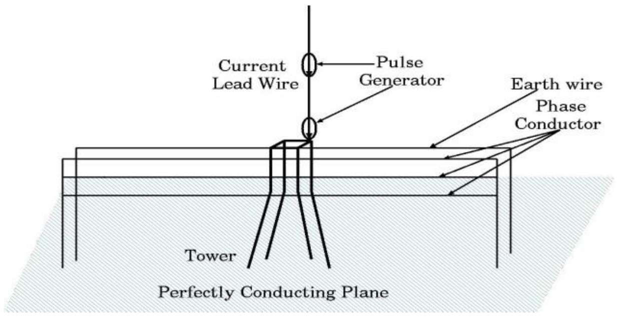


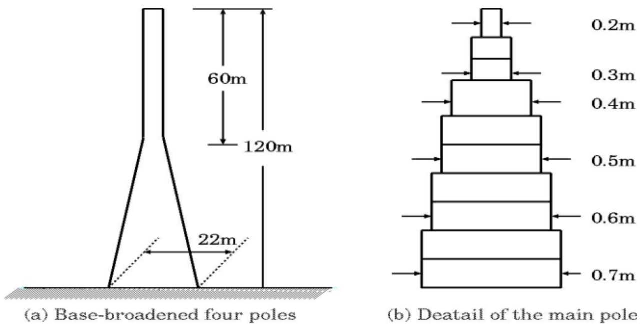
Fig. 16. Schematic diagrams of different types of lightning strokes to the top of a tower.

produces only second-order effects on the surge characteristics of a tower. Therefore the analysis employing a vertical straight wire as a current lead wire which can properly evaluate tower characteristics.

On the other hand, many of the lightning strokes hitting towers on the coastal area of the Sea of Japan in winter begin with upward leaders from the towers [26], and many current pulses are not produced by what are called return strokes [27]. In such kind of strokes, a current wave is thought to propagate down the lightning channel from the cloud to the tower top. For the simulation of this situation, a pulse current generator needs to be remotely placed above the channel. In present analysis, a pulse current generator



(a) Arrangement of tower for simulation



(b) Details of the tower

Fig. 17.The structure of the model tower subjected to analysis.

is inserted into the current lead wire at 240 m from the tower top, where the current lead wire is 480 m in length.

The arrangement for the analysis is as in Fig.17. The model tower shown in above is composed of four main poles. The ground plane was considered perfectly conducting plane of Cupper with conductivity 5.8×10^{7} MHO/M. Each pole is connected to the perfectly conducting plane through 40Ω resistances to realize the tower footing resistance of 10Ω.The impedance seen by a lightning surge flowing from the tower base to true ground. The risk for back-flashover increases with increasing footing impedance. Back flashover occurs when lightning strikes the tower structure or overhead shield wires. The lightning discharge current, flowing through the tower and tower footing impedance, produces potential differences across the line insulation. If the line insulation strength is exceeded flashover occurs i.e. a back flashover. Back flashover is most prevalent when tower footing impedance is high. So, low value of tower footing impedance is desirable in order to avoid back flashover. Compact lines; transmission lines with reduced clearances between phases and between phase and earth and with lower insulation level withstand than for normal lines for the same system voltage. A horizontal earth wire is attached to the tower top at a height of 120 m and phase conductors are stretched at a height of 108 m, 84 m and 60 m respectively, at a distance of 10 m from the tower body. Each conductor or wire is 960 m in length and 0.1 m in radius. The ends of them are stretched down and connected to the ground through matching resistance. This terminating condition does not affect the phenomena within 3.2 μ sec. An insulator voltage is evaluated by flowing current into a 100 kΩ resistive element inserted between the tower body and the phase conductor. To save the computation time, the phase conductor of interest can only be considered, and other phase conductors are removed. The injected ramp input and computed waveforms by simulation

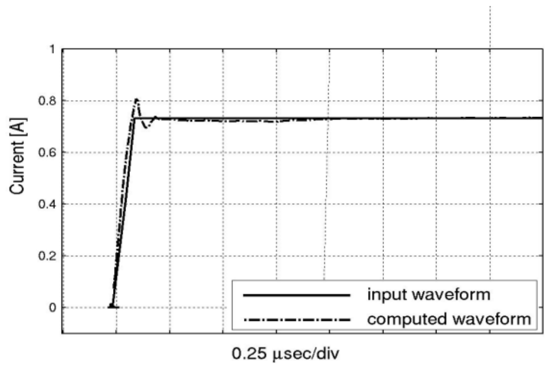
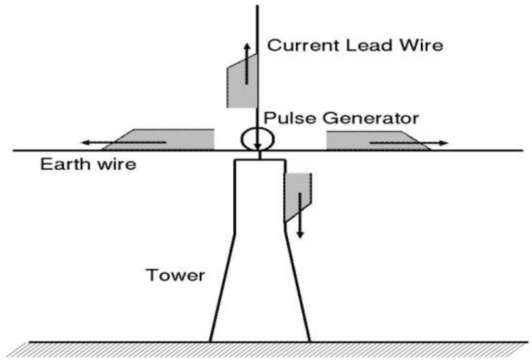
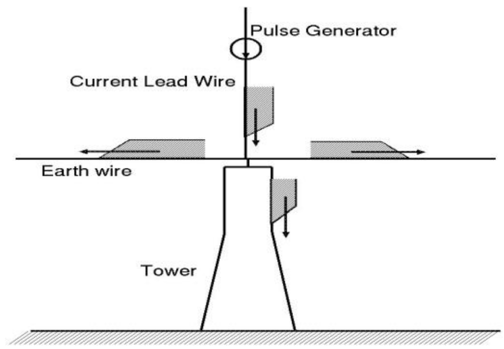


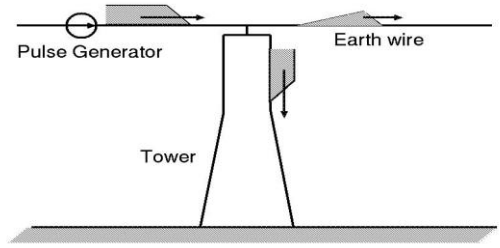
Fig. 18. Comparison of input and computed current waveform.



(a) Return stroke to the tower



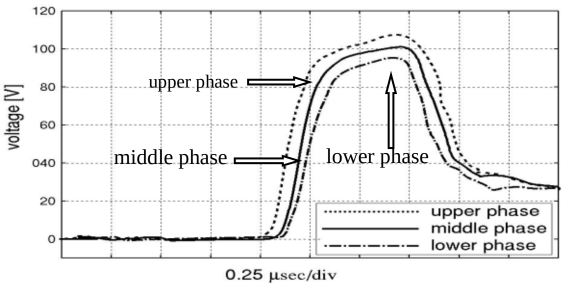
(b) Downward traveling current to the tower



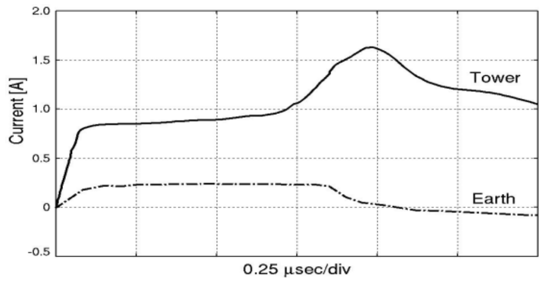
(c) A stroke to the mid-span

Fig. 19. Schematic diagrams for simulation of current splitting ratio between a tower and earth wire

have been shown in Fig.18. Fig.19 illustrates schematic diagram to simulate current splitting ratio between the tower and earth wire. Fig.19 (a) simulates a lightning return stroke to the tower that is called direct stroke or without ground plane, Fig. 19(b) does a downward traveling current to the tower top and Fig. 19(c) does a stroke to the mid-span. Simulation employing Fig. 19(c) have been called the

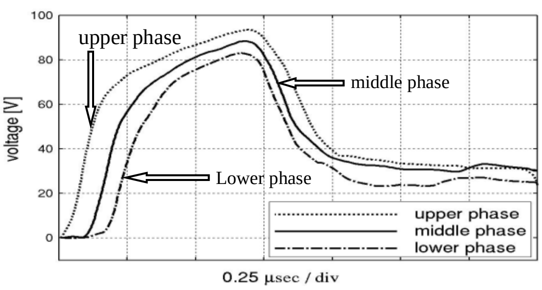


(a) Voltage at different phases

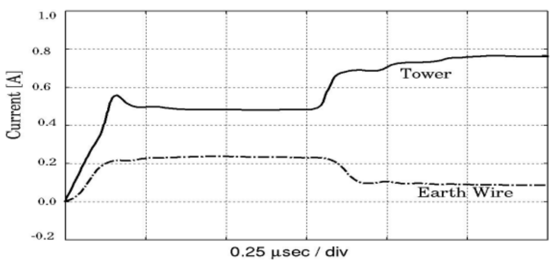


(b) Current in the tower and earth wire due to stroke to mid-span

Fig. 20 Computed waveforms of insulator voltage and splitting current into the tower top in case of horizontal injection.



(a) Voltage at different phase



(b) Current in the tower and earth wire due to return stroke to the tower

Fig. 21. Computed waveforms of insulator voltage and splitting current into the tower top in case of vertical injection.

refraction or with ground plane case. In Fig. 19 (a), a pulse Generator is placed on the tower top and is connected to a long vertical current lead wire, while in Fig. 19 (b); a pulse generator is inserted into the current lead wire at 150 m upward from the tower top. A long earth wire is stretched horizontally. In Fig. 19(c), a pulse generator is inserted into the earth wire at 150 m left from the tower top.

A. WITH GROUND PLANE

Considering the Fig. 19 (c) the simulation was carried out by NEC-2. The output voltage at different phases of

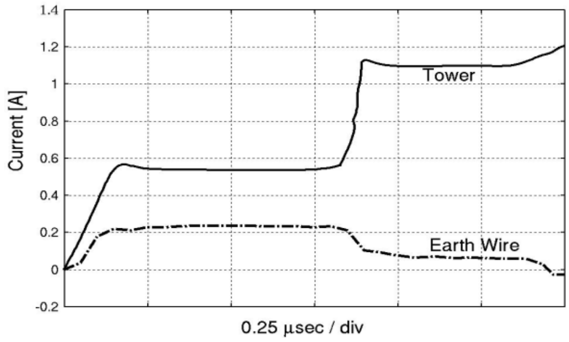


Fig. 22. Computed waveforms of current splitting ratio into the tower and earth wire due to downward travelling current to the tower.

different height and current waveforms were obtained as shown in Fig.20.

B. WITHOUT GROUND PLANE

The simulation was also carried out without ground plane case as shown in the arrangement in Fig. 19 (a). The computed waveforms of voltage and current splitting ratio into the tower and earth wire are shown in Fig.21. The current splitting ratio into the tower and earth wire is also simulated in case of downward traveling current into the tower and computed waveform is shown in Fig.22.

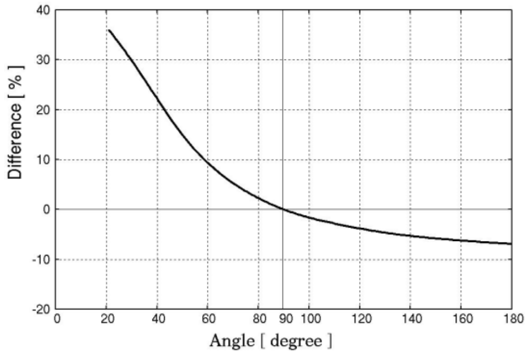
C. SURGE IMPEDANCE CALCULATION

From the Fig. 20 and Fig. 21, for both with and without ground plane cases the tower surge impedances are evaluated at the moment of voltage peak and wave form of current into the tower top in case of vertical injection. In case of indirect stroke the current in the tower is more than indirect stroke. The surge impedances are calculated and summarized in Table II. From the comparison table it is very clear that the surge impedance for the ground plane is naturally much lower than of without ground plane.

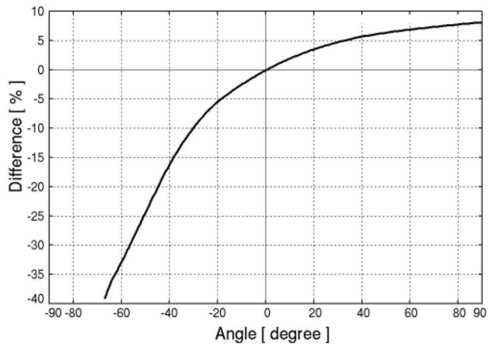
D. INFLUENCE OF THE ARRANGEMENT OF CURRENT LEAD WIRE

The analysis was carried out in different arrangement of the current lead wire as: (i) vertical, (ii) horizontal and perpendicular to a horizontal voltage measuring wire and (iii) horizontal and in extension of a voltage measuring wire. Fig.23 illustrates the effect of the arrangement of current lead wire on the tower surge impedance in details. For the numerical analysis the voltage measuring wire is stretched horizontally. In Fig. 23(a) a current lead wire is in a horizontal plane at the height of the tower and the angle between the current lead wire and the voltage measuring wire is varied from 30^0 to 180^0. The angle of 90^0 corresponds to the case (ii) and that of is taken 180^0 does the case (iii). In Fig. 23(b) a current lead wire is in a plane perpendicular to the voltage measuring and the angle between the current lead wire and a horizontal plane at the height of the tower top is varied from 60 to 90 degree.

Negative sign of the angle shows that the current lead wire is stretched down to the earth. The angle of 90^0 corresponds to the case (i), and that of 0^0 does the case (ii). In both cases tower surge impedance for the case (ii) is selected as the reference value. After calculating the difference the curve of difference verses angle between current lead wire and voltage measuring wire is plotted as shown in figure above. As the angle of injection increasing



(b) Effect of the angle between current lead wire and voltage measuring wire.



(a) Effect of the angle between current lead wire and voltage measuring wire.

Fig. 23. Influence of the arrangement of current lead wire and voltage measuring wire.

TABLE II

Surge impedance of the actual tower model at $t \approx 2h/c$

Arrangement	With ground Plane(Ω)			Without ground Plane(Ω)		
	Upper	Middle	Lower	Upper	Middle	lower
Surge impedance	135	125	107	205	190	170

from 30^0 to 180^0 the surge impedance is decreasing continuously and the difference due to arrangement of the current lead wire becomes greater if the angle between the wires is less than 90^0.

V. ESTIMATION OF SURGE IMPEDANCE OF DOUBLE-CIRCUIT TRANSMISSION TOWER

Fig. 24 illustrates 1000 kV and 500 kV double-circuit transmission towers, which is typical lattice tower used in different countries. The surge impedance of these towers has been simulated by direct method. In this method the earth wires were disconnected. The tower of UHV-I was simulated in the vertical arrangement on a 100-to-1 reduced scale model, and the surge impedance was 200Ω. The others are full-sized towers and were simulated in different arrangements of current lead wire. The surge impedance of these towers for vertical arrangement is summarized in Table III, with the dimensions of the towers. The dimensions of UHV tower indicated that in Table III are those of the original full-sized tower. Here the correction was made by using Fig.23. In the case of UHV-II tower, for example, the current lead wire and the voltage measuring wire on a horizontal plane in the angle of 130^0, it is known from Fig. 23 (a) that the surge impedance of 165 Ω would be 175 Ω if the angle between the two wires were 90^0. This value of 175 Ω corresponds to the condition of 0^0 in Fig. 23 (b), and is again corrected into the condition 90^0, and vertical current injection, yielding 195Ω. It turned out that each of the towers had about the same impedance of 200 Ω as an independent tower, when it was simulated by direct method in the vertical arrangement. Fisher et al. reported the surge impedance of a 345 kV double-circuit transmission tower to be 135 Ω [28] on the basis of the measurement in the vertical arrangement on a 25-to-1 reduced-scale model. The tower surge impedance of a typical double-circuit tower by direct method were characterized by the current split-ting ratio at the top of the tower are estimated to be about 205 Ω for a vertical current injection and about 135 Ω for a horizontal one.

For the numerical analysis, the conductors of the system are divided into 10m or 12m segments. The internal impedance of the pulse generator is 5 kΩ. Computation has been carried out in the frequency range of 39.06 kHz to 20 MHz with the incremental step of 39.06 MHz. This corresponds to the time range of 0 to $25.6\mu\text{sec}$ with $0.05\mu\text{sec}$ increments.

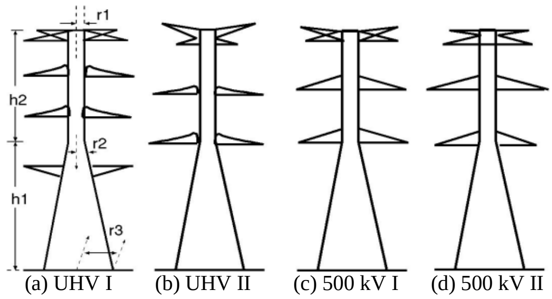


Fig. 24. Structures of 1000 kV and 500 kV double circuit towers.

TABLE III

Surge impedance of various double-circuit towers by direct method with dimension of them

Tower	UHV I	UHV II	500 kV I	500 kV II
$Z_T(\Omega)$ Measured	144	145	148	145
$Z_T(\Omega)$ Simulated	200	195	205	190
r_1 (m)	3.0	2.5	1.5	1.0
r_2 (m)	6.5	4.0	2.3	1.9
r_3 (m)	14	11	5.6	4.0
h_1 (m)	80	60	31	24
h_2 (m)	80	60	31	24

VI. CONCLUSION

Vertical conductor models with and without ground plane for the analysis of surge characteristics theoretically and numerically by NEC-2 has been reported in this research. The applicability of NEC-2 to the electromagnetic field analysis of tower surge response is verified by comparing the computed results with theoretical results on simple structures such as reduced scale model of 60 cm, 90 cm and 120 cm. Simulation has also been carried on actual tower model by NEC-2. Although there are some restrictions in the structures that can be properly modeled for NEC-2, it is much more flexible than the classical modeling of a tower by a cylinder or a cone. Simulation carried out on reduced scale models, therefore, have hardly employed in the practical calculation of the lightning performance of transmission lines but this approach is useful in understanding the lightning phenomena and the dynamic electromagnetic behavior of a three dimensional system struck by lightning particularly at the transient period. The simulation results with NEC-2 are little bit far from the theoretical values, which may due to the effects of programming technique in NEC-2 to calculate currents in wire. The propagation velocity of the electromagnetic wave inside the vertical conductor is found to be same as the velocity of light.

The surge characteristics of an earth-wired tower struck by a lightning are studied with the help of NEC-2. The type of the lighting current influences them, whether it is generated by a return stroke or by a downward traveling current or stroke to mid-span. On the basis of various simulations by NEC-2, the surge impedance of an independent double-circuit tower is estimated to be about 150 Ω when it is evaluated by the direct method, where a current lead wire simulating a lightning channel is stretched vertically and a voltage measuring wire is stretched horizontally. The tower surge impedance representing the current splitting ratio at the tower top for a vertical stroke to the tower is higher than that characterized by the direct method for more than 25 %. On the other hand, the tower surge impedance representing the current splitting ratio for a stroke to mid-span or to an adjacent tower is about 10 % lower than that characterized by the direct method. The difference comes from different electromagnetic field around the tower influenced mainly by the electric fields associated with the fast-front currents propagating the tower, the earth wire and the current lead wire. It is seen that the injected current splits into the tower and earth wire at a fixed ratio until 0.8 μsec, which the arrival time of the reflected wave from the ground. The current splitting into the tower increases gradually before 0.8 μsec. This effect is ascribable to the induced current in the tower. The voltage in the upper insulator rises steeply and then saturates, while the rate of rise in others does less steeply. This is because the upper-phase conductor is more affected by induction from the earth wire whose voltage also rises exponentially. These results can be used to estimate the tower surge impedance of the standard arrangement with a vertical current lead wire and a horizontal voltage measuring wire. Finally, it can also be concluded that this research presents very useful results concerning the simulation of electromagnetic transient in transmission lines caused by direct and indirect strikes of lightning, which will help to design the structure of tower and to design lightning arrester to protect various electric appliances that is used in our everyday life.

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