Analysis of Electromagnetic Transient Program (EMTP) of Lightning Surge of a Vertical Conductor and its Invasion to a Control Building

by

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Abstract

The lightning surge characteristics of transmission line components as well as the statistical data of lightning such as the ground flash density and the stroke peak current distributions are very essential for analyzing the lightning performance of overhead power transmission lines and substations. Lightning over-voltages must be taken into account when designing a vertical tower model and the insulation system of a cable. In the world, specially in Japan various studied, therefore, have been done to measure the characteristics of the line components and to develop their equivalent circuit models for the Electromagnetic Transient Program (EMTP) simulations. EMTP has been widely used in Japan to analyze switching and lightning over-voltages to design power stations and substations from the viewpoint of insulation coordination. The Japanese standard of high voltage testing, JEC-0102-1994, and the insulation design and the coordination of an 1100-kV line of Tokyo electric power company were mostly based on EMTP simulations.

This research demonstrates the electromagnetic behaviour of transient response of lightning surge strike on single vertical conductor, base-broadened tower, actual tower and the control building. Vertical conductor surge responses are analysed using EMTP. The accuracy of this method is shown to be satisfactory with the simulation result based on the numerical electromagnetic code (NEC-2) that were carried out on vertical tower as reduced scale model. Surge impedance is calculated by both the vertical and horizontal stroke analyses method. In addition, line constant program of different frequency of EMTP is also verified in the work for evaluating the voltage and current due to lightning surge.

There have been considerations some methods to evaluate the transient characteristics of a tower, such as : (i) theoretical studies, (ii) simulation of reduced scale models and (iii) simulation of full-sized tower. The simulation analysis of surge response are carried out in the several arrangements of the current lead wire: (i) vertical and at the top of vertical conductor, (ii) vertical and a little far from the top of vertical conductor, and (iii) horizontal and far from the top of vertical conductor. In all the cases, the voltage measuring wire is also placed perpendicular to the current lead wire. Each of the arrangement of the current lead wire affects the measured surge impedance of the vertical conductor and that has been explained in this research in detail. If a travelling wave propagates along the vertical conductor at the velocity of light, the reflected wave from the ground should return to the top of the vertical conductor just after the round-trip time of the travelling wave in the vertical conductor.

1. INTRODUCTION

For radio transmission, telecommunication and overhead transmission lines, lightning is very important cause of unscheduled interruption. In the calculation of the lightning voltages the accurate representation of the transmission tower is a difficult problem and has been the subject of much discussion. Prediction of lightning surges is very important for the design of electric power systems, Radio transmission and telecommunication systems. In particular, tower surge impedance is an important factor in analysis of the lightning performance of transmission lines. Therefore, a number of experimental and theoretical studies on tower surge impedance have been carried out [1]-[17].

The first theoretical formulation of tower surge impedance was proposed by Jordan [1]. It was assumed that the current distribution inside the tower was uniform from the tower bottom to the top of the tower. However, the effect of return stroke current was neglected. The tower was approximated as a vertical cylinder having a height equal to that of the tower, and a radius equal to the mean equivalent radius of the tower. Propagation velocity inside the tower was assumed to be the velocity of light.

In lightning surge simulations the tower models used can range from simple lumped inductances or resistances to complicated non-uniform transmission line circuits. Representation of the tower as a lumped element is only valid if surge current rise time is long compared to surge travels time in the tower.

For measuring the surge impedance of tower, two methods have been used: One is direct method and the other is the refraction or reflection method. Although these two methods are quite different, the difference has not been fully discussed yet. In this work the simulation methods are explained and then the effects of the simulation methods and the arrangements of the measuring wires on the evaluated tower surge impedance are studied with the help of ATP-EMTP.

Simulation methods to investigate the tower surge characteristics include i) Simulation on real towers and ii) Simulation on reduced-scale model. ATP-EMTP is used world wide for switching and lightning surge analysis. ATP is a universal program system for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature. With this digital program, complex networks and control systems of arbitrary structure can be simulated. ATP has extensive modelling capabilities and additional important features besides the computation of transients.

In the measurement by the direct method, the step current is injected into the tower top, and the voltage between the tower top and a voltage measuring wire or the voltage across an insulator string is measured by a voltage divider. The numerical analysis is carried out in the three arrangements of the current lead wire: i) vertical ii) horizontal and perpendicular to a horizontal voltage measuring wire and iii) horizontal and in extension of a voltage measuring wire.

A theoretical work was reported by Ishii and Baba [11]. Recently, the theoretical work was reported by Takahashi [13][14]. He derived the theoretical formula of surge impedance of a vertical conductor including the effect of ground plane and without ground plane. Thus theoretical value of surge impedance agree satisfactory with the experimental and simulation results [15]-[17].

A transmission tower 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 of excitation and the frequencies to be analyzed. There is restriction in the size and the arrangement of individual elements in the analysis by EMTP. Therefore, although fairly complex tower structure can be simulated, some simplification in the geometry is unavoidable to analyze the surge response of a transmission tower. In this work the accuracy of this simulated results is verified with the theoretical value, then this EMTP is applied to the analysis of the surge response of control building.

Among the transmission line components, tower surge characteristics including the tower footing impedance characteristics in the linear region are 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 characteristics become more dominant owing to the longer round-trip time of a travelling wave in the tower. However the agreement on the interpretation of this phenomenon, has not been reached yet.

Measurement on full-sized towers is straightforward in evaluating the actual characteristics of a tower struck by lightning, however it is difficult to carry out this kind of experiments in the ideal arrangement where a current lead wire is stretched vertically above the tower top to simulate a lightning channel, owing to its scale. Measurement on reduced scale models is more economical than full-sized towers, and is flexible in setting up various experimental arrangements. It is however not easy to maintain the accuracy of the measurement. Theoretical studies on simplified geometry may be useful in understanding the phenomenon, however, they are invalid for the accurate evaluation of the dynamic electromagnetic behavior of a three dimensional system struck by lightning.

In the present research, firstly, the applicability of EMTP to the electromagnetic field analysis of vertical conductor surge response is verified by comparison with theoretical results on simple structure.

Secondly, four poles or base-broadened tower model are taken into account for the analysis by EMTP to evaluate the surge characteristics. The effects of the measuring methods and the arrangements of the measuring wires on the evaluated tower surge impedance are studied using EMTP. 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. Thirdly, the surge characteristics of control building struck by lightning are studied with the help of EMTP. The research also presents the method of a lightning surge analysis using the EMTP and related guidelines, and suggests further work to be done based on discussions of applicable limits and problems of the recommended models.

Finally, it can be concluded that this research work presents some 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.

Chapter # 2

Lightning

2. Lightning

2.1 Introduction

Lightning is an electrical discharge in the atmosphere, representing a rapid flow of electrical charge between

(i) a cloud and the ground - CG (Cloud to Ground),

(ii) between two clouds - CC (Cloud to Cloud) or inter cloud lightning,

(iii) between two portions of the same cloud - CC (Cloud to Cloud) or intra cloud lightning.

In this work lightning is the first thing because it acts as a input source for the simulation work for designing the vertical conductor. For reduced scale model very small amount of voltage is considered as surge impedance instead of lightning over voltage.

2.2 Lightning Formation

(i) The conditions needed to produce lightning have been known for some time. However, exactly how lightning forms have never been verified. Leading theories focus around separation of electric charge and generation of an electric field within a thunderstorm. Recent studies also indicate that ice, hail, and semi-frozen water drops known as graupel are essential to lightning development. Storms that fail to produce large quantities of ice usually fail to produce lightning.

(ii) Thunderstorms have very turbulent environments. Strong updrafts and downdrafts occur with regularity and within close proximity to each other. The updrafts transport small liquid water droplets from the lower regions of the storm to heights between 35,000 and 70,000 feet above the freezing level. Meanwhile, downdrafts transport hails and ice from the frozen upper regions of the storm. When these collide, the water droplets freeze and release heat. This heat in turn keeps the surface of the hail and ice slightly warmer than its surrounding environment, and a "soft hail", or "graupel" forms. As the ice particles within a cloud (called hydrometers) grow and interact, they collide, fracture and break apart. It is thought that the smaller particles tend to acquire positive charge, while the larger particles acquire more negative charge. These particles tend to separate under the influences of updrafts and gravity until the upper portion of the cloud acquires a net positive charge and the lower portion of the cloud becomes negatively charged. This separation of charge produces enormous electrical potential both within the cloud and between the cloud and ground. This can accumulate to millions of volts, and eventually the electrical resistance in the air breaks down and a flash begins.

2.2.1 The Most Common Types of Lightning

(i) Cloud-to-ground lightning is the most damaging and dangerous form of lightning. Although not the most common type, it is the one, which is best understood. Most flashes originate near the lower negative charge center and deliver negative charge to earth. However, appreciable minorities of flashes carry positive charge to earth. These positive flashes often occur during the dissipating stage of a thunderstorm's life. Positive flashes are also more common as a percentage of total ground strikes during the winter months.

(ii) Intra-cloud lightning is the most common type of discharge. This occurs between oppositely charged centers within the same cloud. Usually the process takes place within the cloud and looks from the outside of the cloud like a diffuse brightening which flickers. However, the flash may exit the boundary of the cloud and a bright channel, similar to a cloud-to-ground flash, can be visible for many miles.

(iii) Inter-cloud lightning, as the name implies, occurs between charge centers in two different clouds with the discharge bridging a gap of clear air between them.

These various types of lightning causes fire in the forest, voltage surge in the power lines, high electric field and arching inside the building, explosions for industrial sites housing volatile compounds and military sites housing explosives and malfunctioning in telecommunication system or not functioning at all.

2.2.2 Approximate Lightning Parameter [1]

Voltage (relative to ground)	1.0E+8 to 1.0E+9 V
Current	100 A
Peak current	30,000 A
Duration	0.001 - 0.5 s
Diameter of the current channel	0.1 m
Diameter of the luminous region	1-10 m
Typical length	5.0E3 m
Plasma Temperature	3 eV
Electron density	1.0E+23 to 1.0E+24 electrons/cubic meter
% power into visible light	1-3
% power into sound	10-50
% power into heat	10-50
% power into radio waves	10-50
Peak magnetic field created	1000 G

2.2.3 Lightning Effects on Power Systems

The frequency of thunderstorms is important in the protection of power systems. The frequency of occurrence of strokes to transmission lines and open circuit is an indication of the exposure to lightning that an electric power system experiences.

In designing lightning protection for power systems, how lightning enters the system, both by direct strokes and by induced surges from nearby strokes; the propagation of surges within the system; and the effects of these surge voltages and currents on the circuits and apparatus within the system must be considered.

(i) Lightning surges entering a power system through direct strokes are the primary concern in planning surge protection. These strokes may hit phase conductors directly, or they may strike the overhead ground wires or masts that shield the conductors. So, it is necessary to understand the associated surge currents and voltages produced before a protection system can be designed.

(ii) A lightning stroke terminating directly on phase conductors or equipment terminals develops a very high voltage, which, with no surge protection, will flash over the insulation in the majority of cases. If the flashover occurs through air or across porcelain insulation, it rarely causes permanent damage.

a. A lightning stroke terminating near a transmission line can induce a voltage in the circuit, which seldom exceeds 500 kV. Lines, shielded with overhead ground wires and operating at 69 kV and above, generally have sufficient insulation to prevent flashover by voltages in this range. Lower voltage lines, however, with insulation levels appreciably below 500 kV, may be flashed over by induced surges.

b. A lightning stroke terminating on a power system initiates traveling waves, which propagate within the system. To determine the resulting surge voltages and currents in various parts of the system, a traveling wave analysis is required. Simple networks with linear impedances can be analyzed manually; more complicated networks, characteristic of practical power systems, require analog or digital computer analysis. First, consider a stroke terminating on the phase conductor of a transmission line. The stroke initiates voltage and current waves traveling at the speed of light in each direction from the terminating point. With linear impedance, voltage and current have the same waveshape. The traveling waves are represented by the equation: $e = iZ$, where e and i are the voltage and current of the traveling wave and Z is the conductor surge impedance.respectively.

(iii) Surge impedance is circuit impedance as seen by a transient such as lightning. For an open wire conductor:

$$Z = \sqrt{L/C} \qquad \text{(i)}$$

L = inductance/unit length

C = shunt capacitance to ground/unit length

(iv) Typical surge impedance for a line conductor is 400 Ω. Corresponding values for L and C would be 0.4 μH/feet and 2.5 pF/feet, respectively.

(v) Assuming that the stroke current, I, is equal to $2i$ (that is, the stroke current divides equally at the terminating point), the conductor voltage for a 10,000 A stroke is:

$$e = IZ / 2 = \frac{10000}{2} \times 400 \text{ kV} \tag{ii}$$

$$= 2000 \text{ kV}$$

Thus, a traveling wave current of 5,000 A (*I*/2) generates 2,000 kV on the transmission line.

(vi) The traveling waves initiated by the stroke continue to propagate along the line until a discontinuity is encountered. At this point, voltage and current waves are reflected back along the line, and at the same time, traveling waves are transmitted beyond the point of discontinuity. Points of discontinuity may be an open circuit breaker, a transformer, another connected line, or a flashover on the line.

To a lightning surge, a transformer appears as a capacitance and behaves essentially as an open circuit. As the traveling voltage wave encounters an open circuit, a voltage wave of the same magnitude and polarity as the incoming surge is reflected. The incoming and reflected waves combine, resulting in double the traveling wave voltage (*2e*) at the open circuit or transformer termination. This is the well-known phenomenon of voltage doubling at the end of a line.

(a) For an open circuit termination, the reflected current wave has the same magnitude as, but opposite polarity to the incoming waves, resulting in zero current at the open end of a line.

(b) Now consider a line terminated in a perfect short circuit. The incoming and reflected voltage waves have the same magnitude and opposite polarity resulting in zero voltage at the terminal. The current waves have equal magnitude and the same polarity, resulting in double the traveling wave current (*2I*). This is the well-known phenomenon of traveling wave current doubling when it encounters a short circuit.

(c) An arrester discharging a current at the end of a line is a close approximation to the short circuit case, since the arrester resistance is very low compared with the line surge impedance. The current, which the arrester must discharge, therefore, is nearly double the line traveling wave current. This is an important concept in considering arrester discharge duty from lightning surges.

(d) This simple calculation illustrates the advantages of multiple lines in reducing surge voltage in a substation.

(e) As noted previously, typical surge impedance for a phase conductor is 400 Ω. Some other typical values are:

Overhead ground wire – 450 to 500 Ω

Two overheads ground wires (in parallel) – 350 Ω

Steel transmission tower – 200 Ω

Cables – 15 to 40 Ω

(f) The propagation velocity in each of these elements is essentially that of light, with the exception of cables in which propagation velocity is about 50 % of that of light, depending on the dielectric constant of the insulating material. These values are useful in representing power systems in detailed traveling wave analysis using analog or digital computer methods.

(vii) In protecting power systems against lightning, surge voltages and currents must be considered. A lightning stroke to a power system develops very high surge voltages across equipment and line insulation systems. If these voltages exceed the insulation strength, a flashover occurs. A flashover through air or over porcelain insulation (commonly used for transmission line insulation) does not usually produce permanent damage.

(vii) Once lightning enters a power system, the surge current is unlikely to cause any damage. Although the current may be extremely high, it is very short lived and can easily be handled by a small conductor. The size of conductors, installed expressly for conducting lightning currents, is usually determined by mechanical strength considerations, rather than by current-carrying capacity. This is probably due to the stroke channel heating the conductor at the point of impingement, rather than from simply conducting the lightning current.

2.3 History of Lightning Surge Impedance

For overhead transmission lines, lightning is the primary cause of unscheduled interruption. Prediction of lightning surges is very important for the design of electric power systems and telecommunication systems. In particular, tower surge impedance is an important factor in analysis of the lightning performance of transmission lines. Therefore, a number of theoretical studies and experimental on tower surge impedance have been carried out [1]-[10] different times. The formula given by various researcher are given below:

(i) 1934 - Jordan's equation by Jordan of GE

$$Z = 60\{\ln(\frac{2\sqrt{2}h}{r}) - 2.0397\} \tag{iii}$$

(ii) 1956 -Theoretical Formula due to Electromagnetic Field theory by C.F. Wagner

(iii) 1957 - The Theoretical Formula using loop voltage Method by R.Lundholm

$$Z = 60\{\ln(\frac{2\sqrt{2}h}{r})\} \tag{iv}$$

(iv) 1985 - Pointing out about Error of Jordan's Equation by Dr. Okumura of Kyoto University of Japan and Proposal of New Theoretical Equation

$$Z = 60\{\ln(\frac{4h}{r}) - 1\}$$

$$= 60\{\ln(\frac{2\sqrt{2}h}{r}) - 0.653\} \tag{v}$$

(v) 1990 - Experimental Formula by Dr. Hara of Kyoto University

$$Z = 60\{\ln(\frac{2\sqrt{2}h}{r}) - 2\} \quad \text{(vi)}$$

(vi) 1993 - Electromagnetic Field Theory by Takahashi

$$dE = (\mu_0 l_0 c / 4\pi) dx / (ct - x + r_0)^2 \quad \text{(vii)}$$

(vii) 1995 - Theoretical Formula due to Electromagnetic Field Theory by Takahashi

(1) In case without ground plane

$$Z = 60\{\ln(\frac{2\sqrt{2}h}{r}) - 1.540\} \quad \text{(viii)}$$

(2) In case with ground plane

$$Z = 60\{\ln(\frac{2\sqrt{2}h}{r}) - 1.983\} \quad \text{(ix)}$$

From the above it can be described that the first theoretical formulation of tower surge impedance was proposed by Jordan [2]. It was assumed that the current distribution inside the tower was uniform from the tower bottom to the top of the tower. However, the effect of return stroke current was neglected. The tower was approximated as a vertical cylinder having a height equal to that of the tower, and a radius equal to the mean equivalent radius of the tower. Propagation velocity inside the tower was assumed to be the velocity of light.

Theoretical formulations of tower surge impedance based on the electromagnetic field theory were proposed by Lundholm *et al.* [2], Wagner and Hileman [3], Sargent and Darveniza [4] and Okumura and Kijima [5], considering effects of the vector potential generated by the injection current into the tower only.

Another experimental value for actual transmission towers was reported by Kawai [6]. He used a direct method to measure tower surge impedance. His experimental results showed that the tower surge response to a vertical current is different from the response to a horizontal current. Measured propagation velocity inside the tower was 70-80% of the velocity of light.

Scale-model measurements were reported by Chisholm [7] [8] and Wahab *et al.* [9]. Chisholm used the time-domain reflectometry (TDR) method to measure tower surge impedance. These measurements were performed using both horizontal and vertical current injection. Measured propagation velocity inside the tower was 80-90% of the velocity of light. These results showed that the tower surge impedance is strongly influenced by the angle of current injection.

Field measurements on full-scale tower impedance using the direct method were reported by Ishii *et al.* and Yamada *et al.* [10]. These measurements were performed using inclined and horizontal current injection. Both of them proposed surge impedance of the tower based on the Electromagnetic Transient Program (EMTP). Propagation velocity inside the tower was assumed to be the velocity of light.

Numerical work was reported by Ishii and Baba [11][18]. They estimated the surge response of a tower by numerical electromagnetic field analysis. The analysis showed that surge response and surge impedance of the tower depends on the arrangement of the current lead wire.

Recently experimental and simulation result of the surge impedance of single vertical conductor has been obtained using Finite Difference Time Domain (FDTD) method [19]. Thus, computed and experimental values of surge impedance of single vertical conductor are in well agreement with the theoretical values derived by Takahashi.

2.4 The Objectives of the Research:

The purpose of this work are to clarify the surge characteristics of a vertical conductor by analyzing the electromagnetic field around the conductor with the help of EMTP. Equivalent circuit model of the vertical conductor is analyzed by using EMTP. A small scale model is considered for those analysis of a single vertical conductor, base-broadened vertical tower and control building.

Conventional surge problems have successfully been solved by circuit theory, where transmission lines consisting of wires parallel to the earth surface are modeled by distributed-parameter circuit elements and the other components by lumped parameter circuit elements. The distributed parameter circuit theory assumes plane wave propagation that is a reasonable and accurate approximation for the transmission lines, and this assumption enable handling of the electromagnetic wave propagation within the circuit theory. On the other hand, very fast surge phenomena in a 3-D structure, which includes surge propagation in a transmission tower and in a tall building, cannot be approximated by plane wave propagation. In this work the application of EMTP code is discussed for two cases (with the effect of ground plane and without ground plane) of current injection into the vertical conductor. To validate the accuracy and to compare with the theoretical values the results obtained in the EMTP have been taken into account.

In this work, the 3rd chapter includes some fundamental concepts in EMTP when applied to the electromagnetic field analysis of vertical conductor surge response and also the application of EMTP. The 4th chapter is intended to put an EMTP-ATP simulation of the single vertical conductor surge response based on the circuit theory . The comparison of surge response between simulated value and theoretical value of single vertical conductor is also shown in this chapter. The ground and without ground effect, different frequency of line constant program is also investigated in this chapter.

Chapter 5 is discussed with base-broadened four pole vertical conductor. Surge characteristics is analyzed with vertical stroke and horizontal stroke in this chapter. Chapter 6 includes the characteristics of different models of Control Building. In this chapter surge response is considered with different arrangements of the current lead which simulates the lightning channel. And the 7^{th} chapter is very important for practical application, in this chapter the surge impedance is calculated for the actual vertical tower.

The last and finally, Chapter 8 includes the results of the present work are summarized.

2.5 Expected Results

The expected results of this research relate the followings:

. Influence of ground plane on vertical conductor.

. Influence of the frequency effect of line constant program

. Effect of lightning return stroke (direct stroke).

. Effect of stroke to mid span between towers (indirect stroke).

. Dynamic electromagnetic behavior, especially transient response.

. Surge impedance measurement.

. Comparison of simulation result using EMTP with the recently developed theoretical values.

. Surge impedance analysis for base-broadened tower.

. Surge impedance analysis for actual tower.

. Verification of EMTP for Control Building

Chapter # 3

ATP-EMTP

3. Alternative Transients Program Features

3.1 Introduction

Alternative transient program and Electromagnetic transient program (ATP-EMTP) is a universal program system for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature. With this digital program, complex networks and control systems of arbitrary structure can be simulated. ATP has extensive modeling capabilities and additional important features besides the computation of transients.

ATP has been continuously developed through international contributions by Drs. W. Scott Meyer and Tsu-huei Liu, the co-Chairmen of the Canadian/American EMTP User Group. The birth of ATP dates to early in 1984, when Drs. Meyer and Liu did not approve of proposed commercialization of BPA {Bonnevjlle Power Administration) EMTP by DCG (the EMTP Development Coordination Group) and EPRI (the Electric Power Institute). Dr. Liu resigned as DCG Chairman, and Dr. Meyer, using his own personal time, started a new program from a copy of BPA's public-domain EMTP. Requirements of ATP development include honesty in all dealings and non-participation in EMTP commerce. ATP is not in the public domain, and licensing is required before ATP materials are received (refer to Licensing).

3.1.1 Operating Principles

- Basically, trapezoidal rule of integration is used to solve the differential equations of system components in the time domain.
- Non-zero initial conditions can be determined either automatically by a steady-state, phasor solution or they can be entered by the user for simpler components.
- Interfacing capability to the program modules TACS (Transient Analysts of Control systems) and MODELS (a simulation language) enables modeling of control systems and components with nonlinear characteristics such as arcs and corona.
- Symmetric or unsymmetric disturbances are allowed, such as faults, lightning surges, any kind of switching operations including commutation of valves.
- Calculation of frequency response of phasor networks using FREQUENCY SCAN feature.
- Frequency-domain harmonic analysis using HARMONIC FREQUENCY SCAN (harmonic current injection method)

- Dynamic systems also can be simulated using TACS and MODELS control system modeling without any electric network.

3.1.2 Components

- Uncoupled and coupled linear, lumped R,L,C elements.
- Transmission lines and cables with distributed and frequency-dependent parameters.
- Nonlinear resistances and inductances, hysteretic inductor, time-varying resistance, TACS/MODELS controlled resistance.
- Components with nonlinearities: transformers including saturation and hysteresis, surge arresters (gapless and with gap), arcs.
- Ordinary switches, time-dependent and voltage-dependent switches, statistical switching (Monte-Carlo studies).
- Valves (diodes, thyristors, triacs), TACS/MODELS controlled switches.
- Analytical sources: step, ramp, sinusoidal, exponential surge functions, TACS/MODELS defined sources.
- Rotating machines: 3-phase synchronous machine, universal machine model.
- User-defined electrical components that include MODELS interaction

3.1.3 Program Capabilities

ATP-EMTP tables are dimensioned dynamically at the start of execution to satisfy the needs of users and their hardware (e.g., RAM). No absolute limits have ever been observed, and the standard version has limits that average more than 20 times default table sizes. Today, the largest simulations are being performed using Intel-based PC's. The following table shows maximum limits for standard EEUG program distribution.

Busses	6000
Branches	10000
Switches	1200
Sources	900
Nonlinear elements	2250
Synchronous machines	90

3.1.4 Typical Applications

ATP-EMTP is used world-wide for switching and lightning surge analysis, insulation coordination and shaft torsional oscillation studies, protective relay modeling, harmonic and power quality studies, HVDC and FACTS modeling. Typical EMTP studies are:

- Lightning overvoltage studies
- Switching transients and faults
- Statistical and systematic overvoltage studies
- Very fast transients in GIS and grounding
- Machine modeling
- Transient stability, motor startup
- Shaft torsional oscillations
- Transformer and shunt reactor/capacitor switching
- Ferroresonance
- Power electronic applications
- Circuit breaker duty (electric arc), current chopping
- FACTS devices: STATCOM, SVC, UPFC, TCSC modeling
- Harmonic analysis, network resonances
- Protective device testing

3.1.5 Program Developers

W. Scott Meyer was born in Madison, Minnesota, USA, in 1942. Dr. Meyer joined the Bonneville Power Administration (BPA) in Portland, Oregon -an agency of the U.S. government.

Since late 1972, he has been preoccupied with the digital computer simulation of electromagnetic transients. Early milestones along this 29-year evolution include the discovery of machine translation (to make the program run on all computers of common interest) in 1974, and creation of the name EMTP in 1975. In March of 1995, Dr. Meyer formally retired from BPA, and today works on ATP development with BPA's Dr. Tsu-huei Liu as an unpaid BPA Volunteer.

Most of the years since 1975 have been absorbed in work on EMTP, although the duties of management have been a distraction during two intervals. First, between 1982 and 1988, Dr. Liu supervised those who were involved with reliability programming, and also EMTP. Second, since 1991, Dr. Liu has served as Manager/Team Lead of the larger Planning Software Support group within System Planning/Network Planning at SPA. Today, this has responsibility not only for EMTP, but also for programs that are used for load flow and transient stability studies.

Several experts around the world have been contributing to EMTP starting in 1975 and later to ATP in close cooperation with Drs. W. Scott Meyer and Tsu-huei Liu.

3.2 Fundamental description about different transmission lines.

3.2.1 Lossless Line Model

This model represents a tower by a lossless uniform transmission lone having the length of the tower height . Although this simple representation may be suitable for the simplified estimation of lightning back-flashover probabilities [27] , it cannot reproduce the complex waveforms of insulator voltages.

3.2.2 Distortion-less Line Model

This model represents a tower by a uniform transmission line having constant attenuation. The representation by the surge impedance Z_T =100 Ω ,The surge propagation velocity in the tower v=0.7c and the surge attenuation coefficient γ =0.7 [28], which has been used in the estimation of lightning performance of transmission lines in Japan, is included in this category. The constant attenuation coefficient results in high residual tower voltage as time elapses, so that the wave tail of the reproduced tower voltage deviates from the actual value.

3.2.3 Model Composed of many Loss-less Lines

This model is composed of many short loss-less lines that represent vertical elements, slant elements and crossarms elements as illustrated in Fig. 1. The surge impedance of each part is determined from their dimensions and geometry, which is based on a series of experiments on reduced scale models of independent towers.

The surge impedance of each line representing vertical elements Z_{T1},Z_{T2}, Z_{T3} and Z_{T4} , is given by

$$Z_{Tk} = 60\left(\ln\frac{2\sqrt{2}h_k}{r_{ek}} - 2\right), \qquad (K = 1, 2, 3, 4.) \qquad (x)$$

where $$r_{ek} = 2^{1/8}(r_{Tk}^{\frac{1}{3}} r_B^{2/3})^{1/4}(R_{Tk}^{1/3} R_B^{2/3})^{3/4}, \qquad (K = 1, 2, 3, 4.)$$

in which h_K, r_{Tk}, R_{Tk}, r_B and R_B are the lengths of the corresponding parts indicated in Fig.1.
The surge impedance of each line representing slant elements, Z_{L1}, Z_{L2}, Z_{L3} and Z_{L4} is given by $Z_{Lk}=9Z_{TK}$. (K = 1, 2, 3, 4). The travel time in these lines is 1.5 times of those representing vertical elements. The surge impedance of each line representing crossarms Z_{A1}, Z_{A2}, Z_{A3} and Z_{A4}, is given by

$$Z_{Ak} = 60\ln\frac{2h_k}{r_{Ak}}, \qquad (K = 1, 2, 3, 4.) \qquad \text{(xi)}$$

Where h_k and r_{Ak} are the height and the equivalent radius of kth crossarm, respectively. The length of each line of the crossarm is set equal to the actual arm length. The equivalent radius is chosen as ¼ of the width of the arm at the junction point.

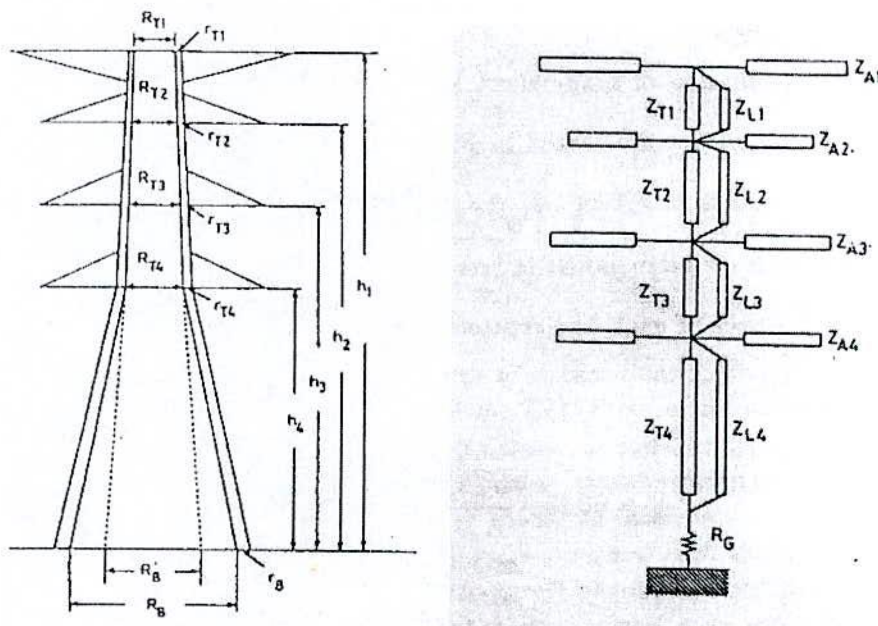


Fig. 1 Tower Model Proposed by by Hara et al.

3.3 Different types of Simulation Methods

3.3.1 Tower Surge Impedance Using Measuring Method

For simulation the surge impedance of towers, two principal methods have been used: one is the direct method and the other is the refraction or the reflection method. Although these two methods are quite different, the difference has not been fully discussed yet.

Simulation of tower surge using direct method [6][14], the step current is injected in to the tower top and a voltage measuring wire or the voltage across an insulator string is measured by a voltage divider as illustrated in Fig. 2. Measurements on the full-sized towers by the so-called direct method have been carried out mainly in Japan [6][10][13] to evaluate the tower surge characteristics. The top voltages or the insulator voltage measured by this method gradually rises until the reflected wave from the ground arrives and then it decreases. The tower surge impedance is defined as the ratio of the instantaneous value of the voltage to the current flowing in to the tower at the moment of the voltage peak.

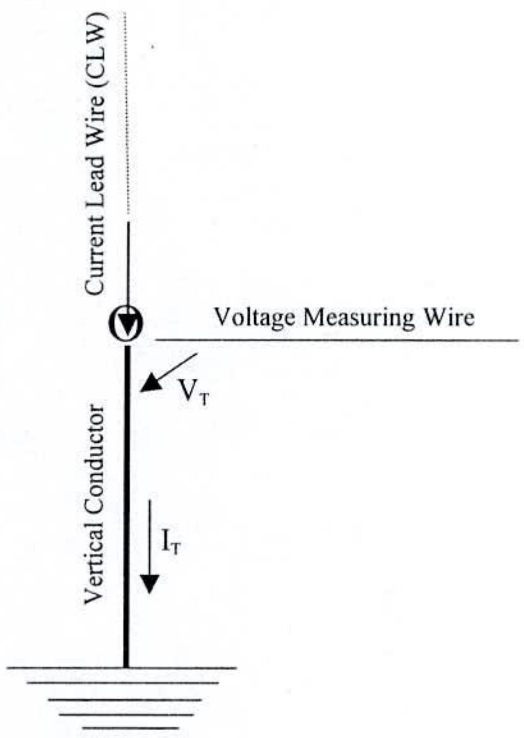


Fig. 2 Simplified Diagram of the measurement by the direct method of Vertical Conductor.

This method is straightforward in evaluating the insulator voltage when the tower is struck by a lightning stroke. In the measurement of actual tower, however, it is difficult to stretch a current lead wire vertically from the tower top. Therefore, the geometrical arrangements in measurements so far are somewhat different from the incident of lighting striking a tower, where the current lead wire acts as a vertical lighting channel.

In the measurement by the refraction or the reflection method [15][16], a wire to guide a steep front current wave is connected to the top of a tower under measurement and the refracted or the reflected wave on the measuring wire is observed to estimate the transient impedance at the tower top. This method is considered valid in evaluating refraction and reflection of surges, associated with mid-span strokes or strokes to adjacent towers at the connecting point of the tower and the earth wires.

The tower surge impedance characterized by this method is qualitatively different from the transfer impedance characterized by the direct method, therefore, the value by the refraction method does not necessarily agree with that the direct method.

3.3.2 Arrangement of the Current Lead wire and voltage Measuring Wire

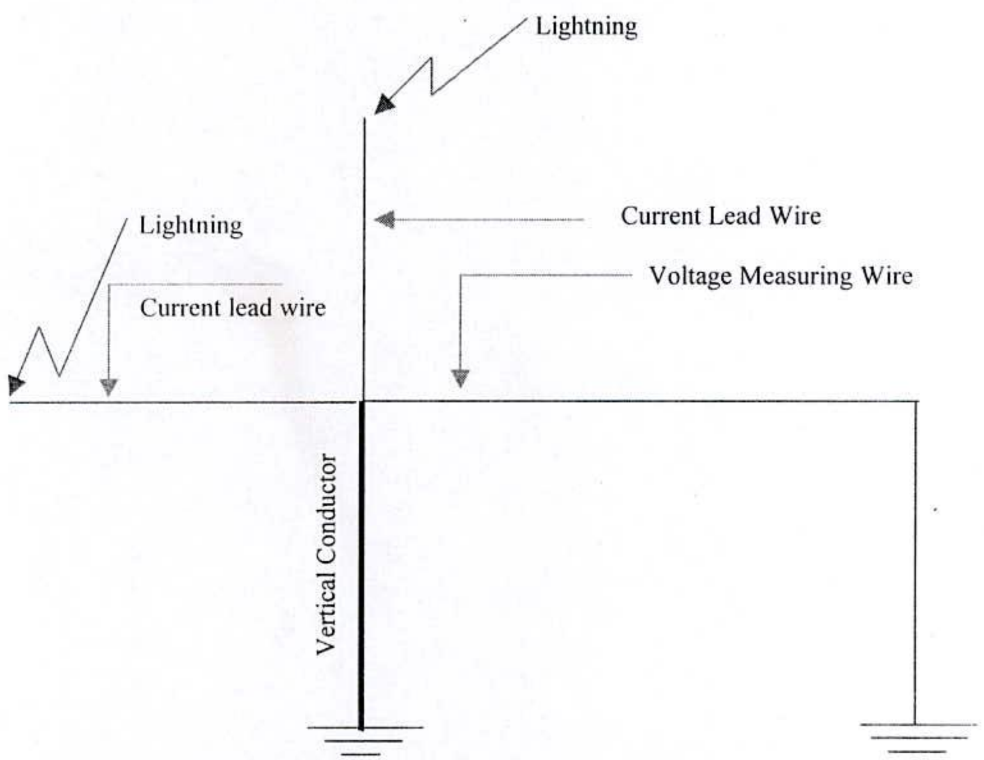


Fig. 3 Arrangement of the Voltage Measuring wire and Current Lead wire.

It is shown in the Fig. 3, that the arrangement for the numerical analysis simulating the measurement by the measuring method. The analysis is carried out in the three arrangements of the current lead wire which is already given: i) vertical, ii) horizontal and iii) horizontal and in extension of a voltage measuring wire.

In this model it is chosen the current lead wire is from 2 m to 6 m length and the voltage measuring wire from 2m to 5 m long and its diameter is 0.16 cm . A rectangular pulse current is applied on the tower top and connected to the current lead wire. In this paper the tower top voltage is defined as the voltage between the tower and the voltage measuring wire and it is evaluated through the current flowing a 50 kΩ resistive element inserted between them.

3.3.3 Effect of the Arrangement of Current Lead Wire

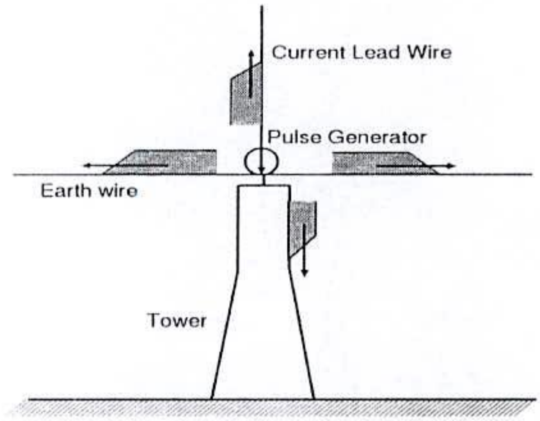
Figure 3 shows the arrangement for the analysis simulating the measurement by Electromagnetic Transient Program (EMTP) . The analytical arrangement is carried out in the three arrangements of the current lead wire. i) vertical ii) horizontal and iii) horizontal with termination with the ground. The voltage measuring wire is normally 2 to 5 m length and the current lead wire is also like this. The radius of the wire is about 0.08 to 0.05 cm and the voltage is applied on the top or mid-span of the tower having the internal impedance of 50 kΩ is inserted on the tower top and connected to the current lead wire. In this work the tower top voltage is measured as the voltage between the tower top and the voltage measuring wire and it is evaluated through the current flowing a 50 kΩ resistive element is inserted between them.

Fig. 3 illustrates the tower structure subject to analysis. The tower height is of 2 m and the radius of the tower is 0.08 cm. In this work the current lead wire is taken from 0.3 m to 3.3 m and the voltage measuring wire is taken from 2 m to 5 m for simulation purpose. Then the voltage is applied in the tower top and some times mid-span of the tower. This simplest structure allows accurate numerical analysis and is convenient to study the effects of measuring wire. For the analysis the conductors of the system are divided into different segments. Computation is carried out varying line-constant frequency 1 ns to 4 ns and total pulse width is 40 ns.

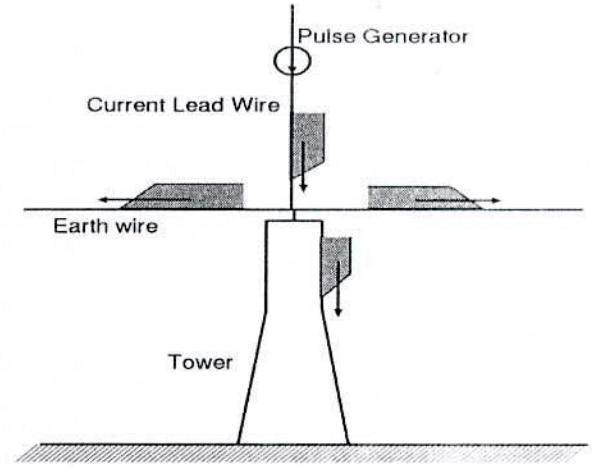
3.3.4 Simulation Parameters

In this research different parameters are used in the line constant program and input file for simulation of the work. Frequency is 1.953×10^6 Hz is taken in the line constant program, rise time is 1 ns and total pulse width is taken for 40 ns in the input (EMTP) program. Again internal source impedance for voltage measuring wire is taken 50 KΩ and footing impedance is only 50 Ω. 5 V is applied at the top of the vertical tower instead of lightning over-voltage as the input source.

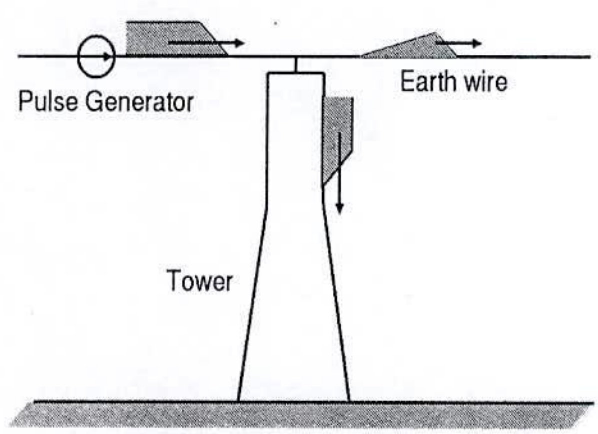
3.3.5 Tower Surge Impedance Using Refraction Method



(a) Return stroke to the tower.



(b) Downward travelling current to the tower.

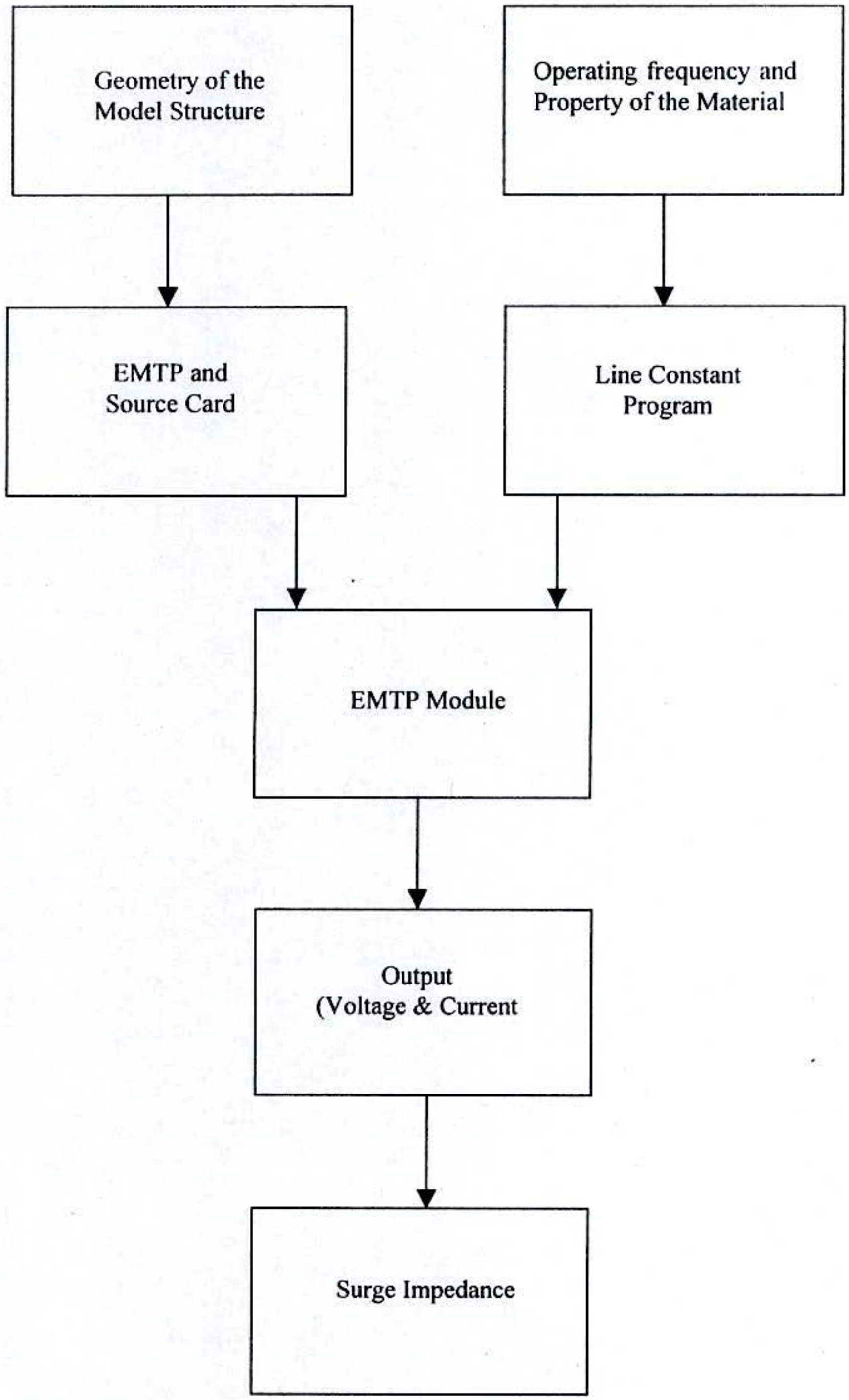


(c) Stroke to mid-span.

Fig. 4 Schematic diagram for simulation of current splitting ratio between a tower and earth wire.

Figure 4a illustrates schematic diagram to simulate current splitting ratio between the tower and earth wire. Fig. 4a simulates a lightning return stroke to the tower that is called direct stroke or without ground plane, Fig. 4b does a downward travelling current to the tower top and Fig. 4c does a stroke to the mid-span. Simulation employing Fig. 4c have been called the refraction or with ground plane case. It is shown in the Fig. 4a. a pulse generator is placed on the tower top and is connected to a long vertical current lead wire, while in Fig. 4b 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. 4c , a pulse generator is inserted into the earth wire at 150 m left from the tower top.

3.3.6 Flow Diagram of Simulation Works



Chapter # 4

Single Vertical Conductor

4. Single Vertical Conductor Models for EMTP Analysis.

4.1 Introduction

The Electromagnetic Transients Program (EMTP) is probably the most widely used power system transients simulation program in the world today. In this section, the EMTP simulations based on the circuit theory were performed for the single vertical conductor model with ground plane and without ground plane [21]-[24]. In the circuit model, the line was represented by a distributed R-L-C circuit with skin effect being neglected. The NEC-2 cannot exactly model the structures of actual towers or vertical conductors, and in addition it cannot directly interfaced with the EMTP. For the EMTP simulations, therefore, it is practical to employ an equivalent circuit of the transmission-line type for representing the vertical conductor system. In developing the model or in determining its parameters, characteristics stated in the preceding chapter should be taken into consideration. In this chapter, vertical conductor models used so far are reviewed with emphasis on their performance in reproduction of measured waveforms of current through the vertical conductor and voltage at the top of it. The surge impedance is then calculated from the ratio of the maximum potential at the conductor top to the current through it at the time of voltage peak.

4.2 Modeling Guidelines and Structures

In this section the author works with seven models, they are :

i) 2 m vertical tower plus 3.3 m vertically extended current lead wire with 2.3 m voltage measuring wire ii) 2 m vertical tower plus 6 m vertically extended current lead wire with 2.2 m voltage measuring wire iii) 2 m vertical tower plus 3.3 m vertically extended current lead wire with 5m voltage measuring wire. iv) 2 m vertical tower plus 3.3 m vertically extended current lead wire with 2.3 m voltage measuring wire with different line constant frequency v) 2 m vertical tower plus 2 m horizontally extended current lead wire with 2.2 m voltage measuring wire for ground effect and without ground effect. vi) 4 m base-broadened tower plus 0.5 m vertically extended current lead wire with 2.2 m voltage measuring wire vii)) 0.6 m vertical tower plus 2 m vertically extended current lead wire with 2.3 m voltage measuring wire

4.3 Analysis of Single Vertical Conductor

The nature of voltage , current and surge impedance are analyzed for all the models discussed in Art. 4.2. The simulation employing a different method of current injection using Electromagnetic Transient Program (EMTP) , where a voltage or pulse current generator is applied at the top of the current lead wire. The setup for the numerical analysis is illustrated in Fig. 5, Fig. 8 and Fig. 17. The cases for the two arrangements of the current lead wire are simulated i.e. one is vertically applied voltage and another is horizontally applied voltage into the current lead wire.

The arrangement for the simulation works of vertical conductor whose voltage injection is at the top of the current lead wire is shown in the Fig. 5. In this model 2 m single vertical conductor is taken and the voltage measuring wire, current lead wire is also shown in the figure. Again its equivalent circuit is also given for easy simulation of voltage, current and surge impedance characteristics. In the following figure shown vertical conductor is divided into four segments and the voltage is applied at the top of the current lead wire. By varying current lead wire up to 6 m simulation result is taken using EMTP.

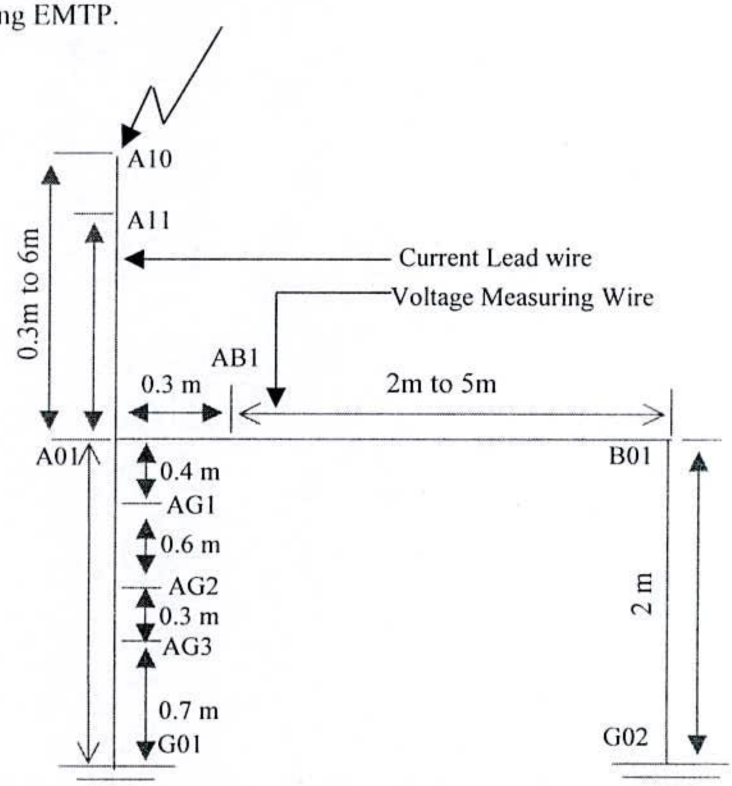


Fig. 5 Single vertical conductor with vertically applied voltage

Figure 6 shows the equivalent circuit representation for the vertical conductor system considering with the existence of ground plane and without ground plane [21]-[24]. The dimensions of these circuit models are the same as considered for the simulation and experimental model systems of Fig. 5. The voltage sensors and the current sensors indicated in Fig. 6 and Fig. 18 represent the measuring points. FH represents the single vertical conductor. Location of injected current is shown by the mark P and H with ground and without ground plane respectively.

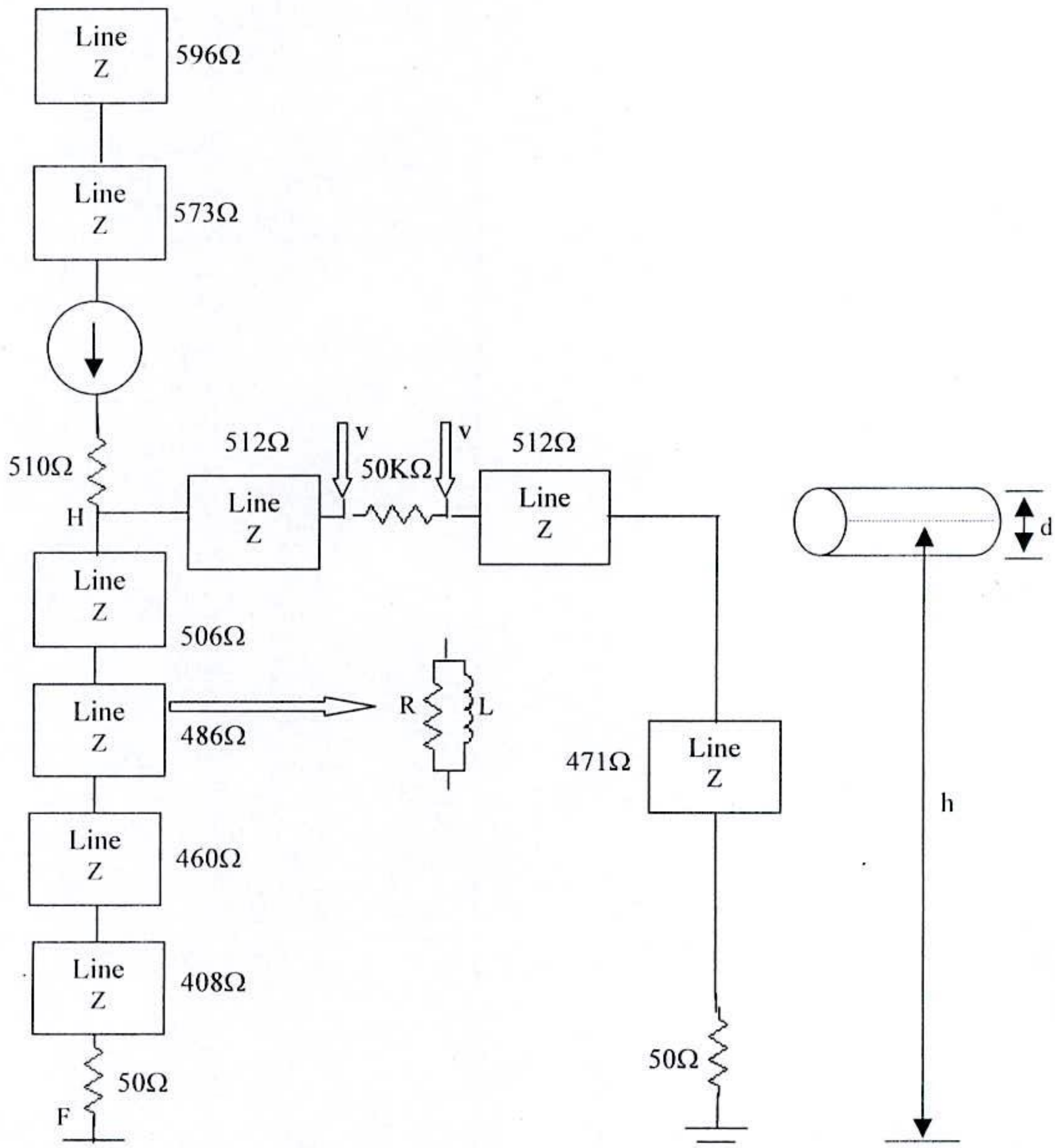


Fig. 6 Equivalent circuit of single vertical conductor

The values indicated at the right side of FH, represent the surge impedances at the corresponding line segment and are calculated by the line constant shown in Appendix. These surge impedances of the distributed line and velocity of wave propagation as well are used as the input data for the EMTP analysis of voltages and currents. Different values of surge impedances are due to the different height of the conductor segment. The vertical conductor FH is considered four segment of 0.4 m, 0.6 m, 0.3 m and 0.7 m respectively to represent upper, middle and lower currents. The EMTP simulations were performed for two models of the system. In the first, the simpler model, the line was represented by a distributed R-L-C circuit with the skin effect and finite ground conductivity being neglected. In the second, more complex model, frequency dependent line parameters (considering an imperfect ground and the skin effect). As there is no parallel conductor with the single vertical conductor system, there is no mutual effects and for that reason, frequency dependent parameter is not considered here.

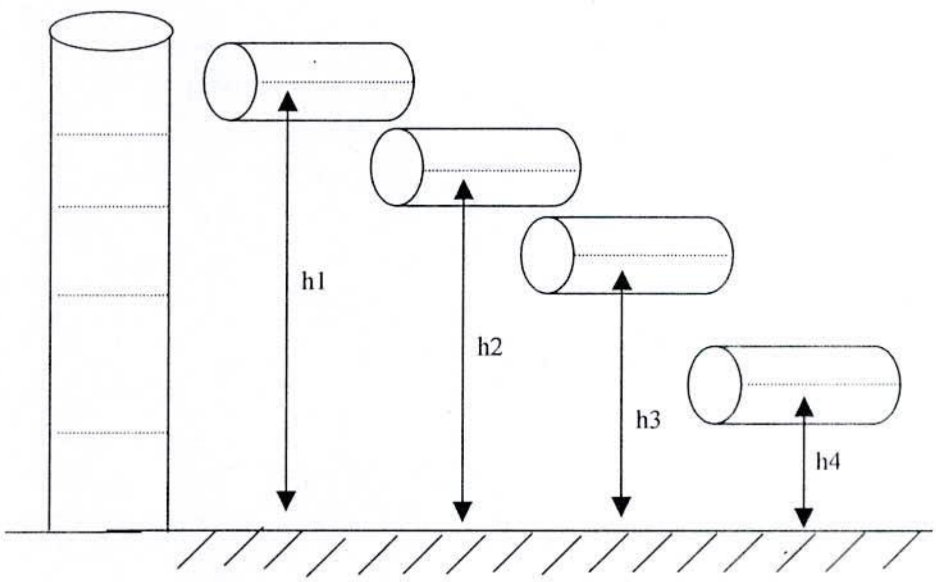


Fig. 7 Consideration for Perpendicular Conductor

As the analysis with EMTP, it can be easily handled to the horizontal conductor but cannot be handled just as it is to the perpendicular conductor. Therefore, to solve the problem, the perpendicular conductor can be divided into the horizontal conductors as it makes a center level at the axis in each conductor as shown in Fig. 7. The input data for the EMTP is given in Appendix.

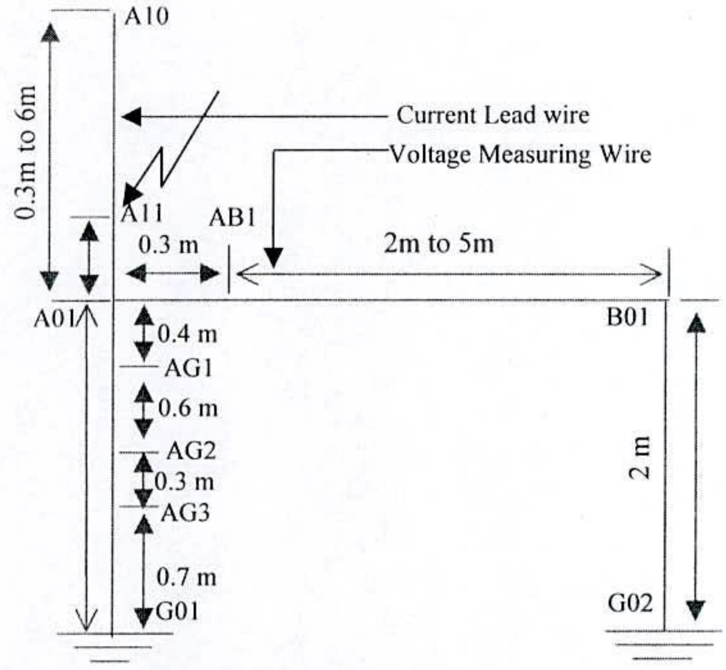


Fig. 8 Vertical Conductor, Voltage applied at the lower segment of the Current Lead wire

4.4 Influence of the method of Current Injection

If the surge current propagates along the tower at the speed of light, the reflected wave from the ground should return to the tower top after twice of the tower travel time which is 13 ns for the structure of the model of Fig. 5 But in the simulated results of Fig. 9b and Figs. 11a, 11b the voltage waveforms reach their peaks about 4 and 5 ns respectively and fall at 7ns after the beginning, which indicates that a negative voltage wave arrives at the tower top before the arrival of the reflected wave from the ground.

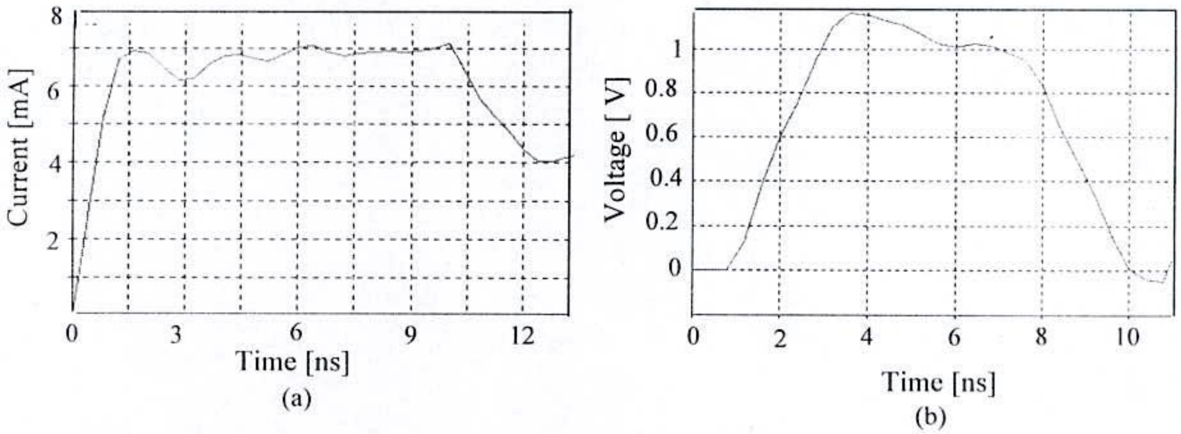


Fig. 9 (a) Injected Current of for single vertical conductor, (voltage applied vertically at the upper segment of the channel) (b) Simulation voltage of same model.

This phenomenon occurs because the electromagnetic wave in TEM mode illuminates the structure by the method of current injection illustrated in Fig. 10a In this case, the electromagnetic wave of excitation arrives at the tower foot simultaneously with the arrival of the tower top and a negative voltage wave is induced at the tower foot before the occurrence of the reflection of the voltage wave propagating down from the tower top. This induced wave is observed in the current waveforms in Fig. 10a as the gradual increase of the current before 13ns.

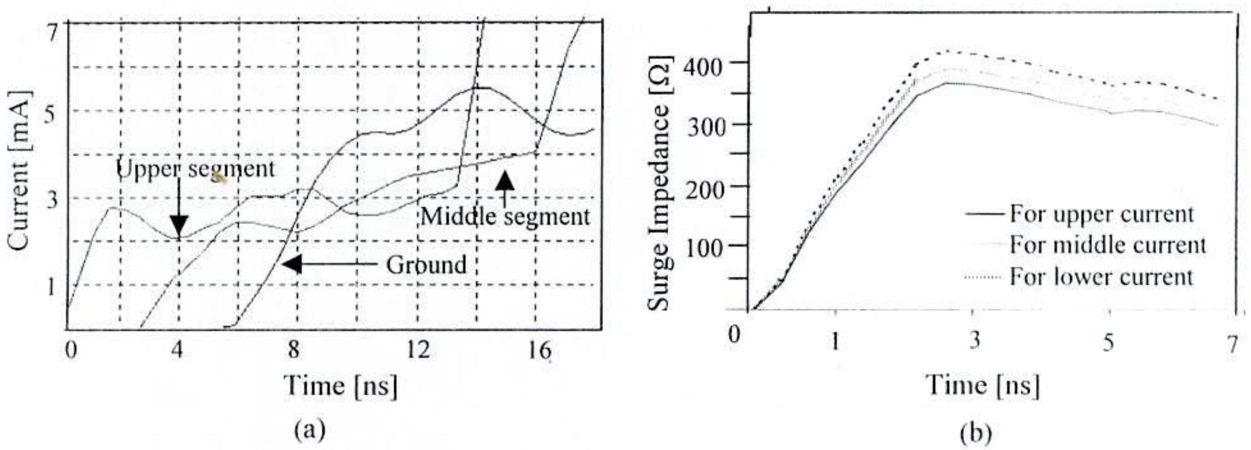


Fig. 10 (a) Upper and middle segment and ground current of vertical conductor (voltage applied vertically at the upper segment of the channel), (b) Surge impedance of same model.

From this induction is observed in the current wave-shape in Fig. 10a as the gradual increase of the current at 10 ns. The tower surge impedance for these case are evaluated at 4 ns, 9 ns and 13 ns respectively from the current wave-shape of input tower current. The tower surge impedance is calculated from the voltage wave-shape of the Fig. 9b are summarized in Table 1.

Table:1

	For upper current	For middle current	For lower current
Surge Impedance	362 Ω	387 Ω	415 Ω

4.5 Voltage Analysis of Single Vertical Conductor with Vertical Injection, Varying Current Lead Wire and Voltage Measuring Wire

For measuring the voltage, current and surge impedance using return stroke and downward travelling current to a tower, another model shown in the Fig. 8. In this section only voltage characteristics is explained of the model of Fig. 5 and Fig. 8. The different characteristics of voltage shapes are shown below.

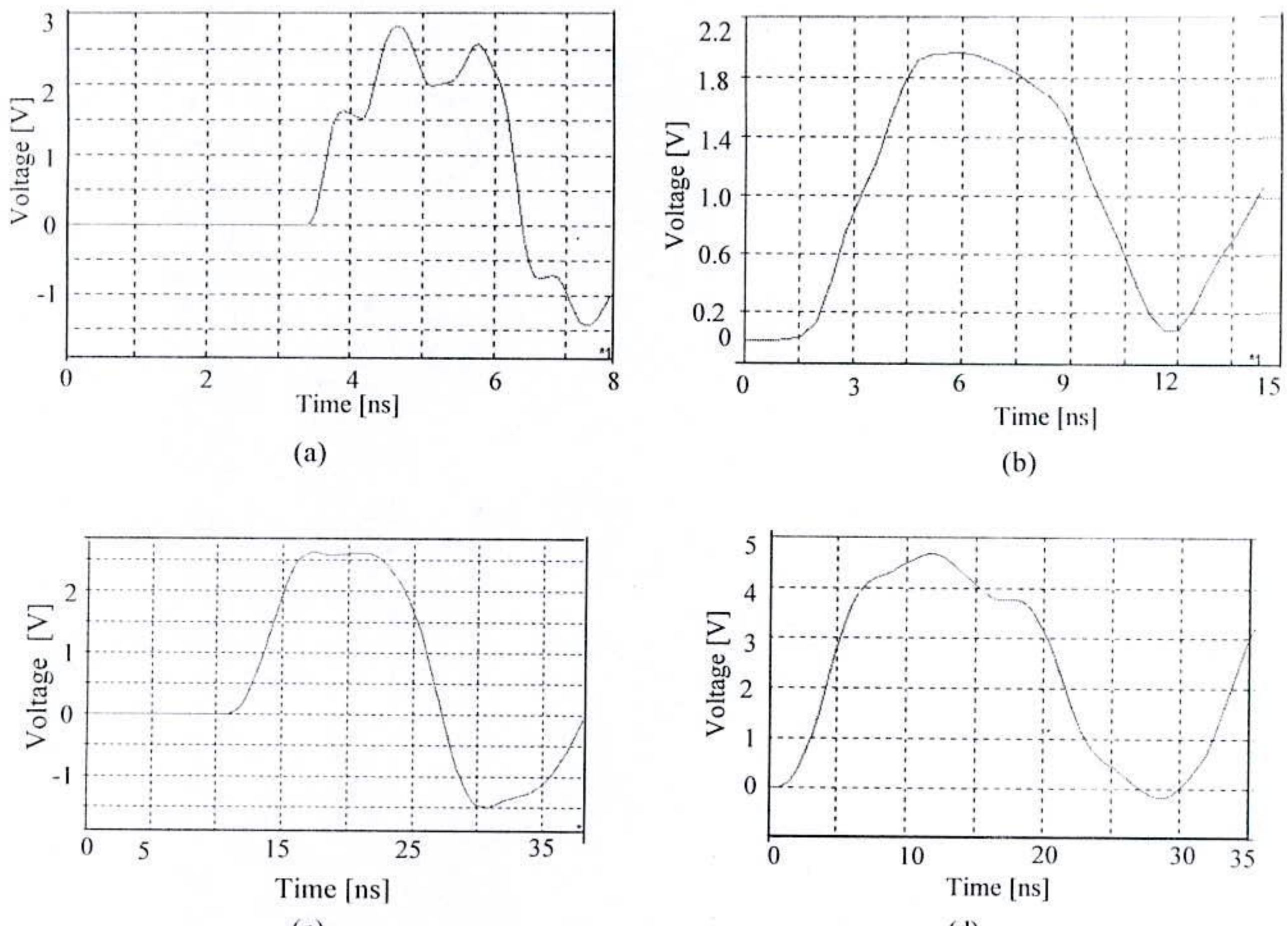
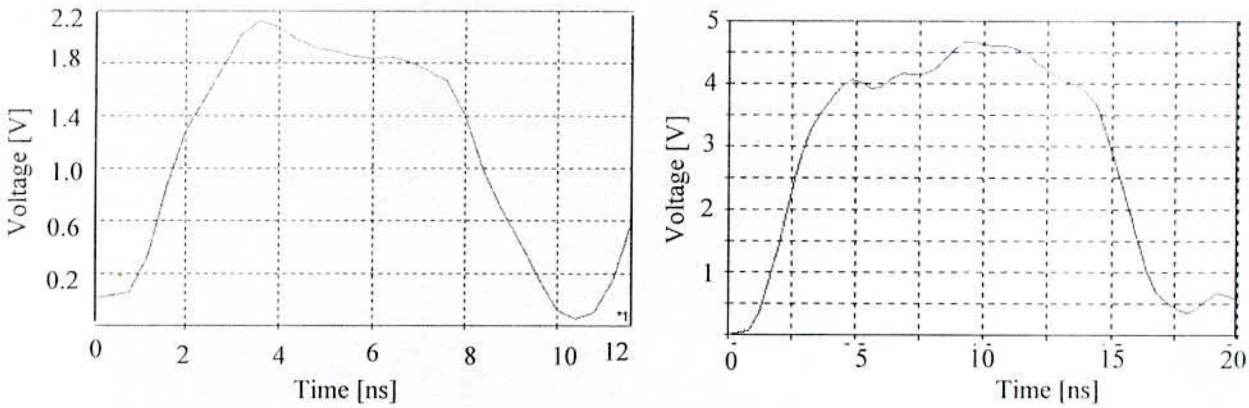


Fig. 11 (**a**) Simulated voltage of vertical conductor. (voltage applied vertically at the top the channel, channel length- 6 m), (**b**) Simulated voltage of same model, channel length- 3.3 m), (**c**) Simulated voltage of same model, channel length- 3.3 m and voltage measuring wire-4.3 m)), (**d**) Simulated voltage of same model, channel length- 0.3 m and voltage measuring wire-5.3 m).



(a) (b)

Fig. 12 (**a**) Simulated voltage of vertical conductor. (voltage applied vertically at the lower segment of the channel, channel length- 3.3 m and voltage measuring wire-2.2 m) (**b**) Simulated voltage of same model, voltage applied vertically at the upper segment of the channel.

From the combinations of the model, it is shown that model of Fig. 5, 5V is applied at the top of the current channel and the model of Fig. 8, 5V is applied at the lower segment of the current channel. The current channel is shown in Fig. 5 that varies from 0.3 m to 6 m, so there will be some delay time in the voltage waveform before the beginning of rising point.

So that from the above voltage waveform of simulated voltage curve of Figs. 9b, 11a and 11b are shown that voltage rises at 6 or 7 ns and fall at 8 ns, but the falling time should be at 13 ns. That is if the surge current propagates along the tower at the speed of light, the reflected wave from the ground should return to the tower top after twice of the tower travel time which is 13 ns for the structure of the model of Fig. 5 which indicates that a negative voltage wave arrives at the tower top before the arrival of the reflected wave from the ground.
For this some modification has to be done of the models of Figs. 5 and 8, i.e. in the models voltage measuring wire increased to 4 m and 5 m instead of 2.3 m and the Current channel wire reduced to 0.3 m instead of 3.3 m.

So that from the voltage waveform of Fig. 11c and 11d are shown that voltage rises at 11 ns to 12.7 ns , which indicates approximately equal to the calculated value 13 ns. So the simulation voltage both of the models of Fig. 5 and Fig. 8 are correct in reduced scale model.

4.6 Current analysis of Single Vertical Conductor with Vertical Injection Varying Current Lead Wire and Voltage Measuring Wire

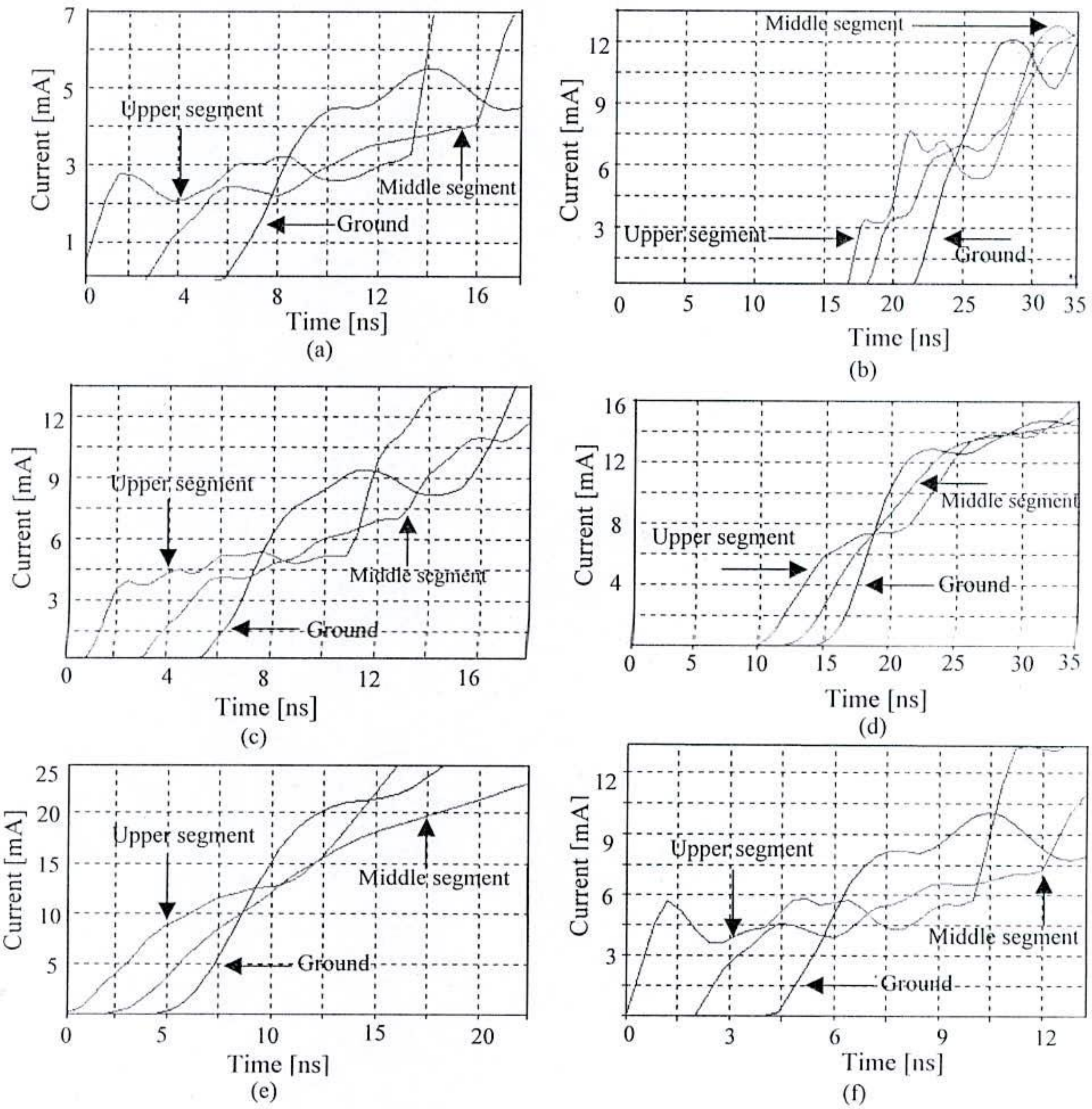


Fig. 13 (**a**) Upper and middle segment and ground current of vertical conductor. (voltage applied vertically at the top of the channel, channel length- 3.3 m, (**b**) Same Current, channel length- 6 m , (**c**) Same Current (voltage applied at the lower segment of the channel, length- 3.3 m, (**d**) Same Current (voltage applied at the top of segment of the channel, length- 3.3 m, and voltage measuring wire-4.3 m, (**e**) Same Current (voltage applied at the top of the channel, length- 3.3 m and voltage measuring wire-5.3 m), (**f**) Same Current (voltage applied at the lower segment of the channel, length- 3.3 m and voltage measuring wire-5.3 m).

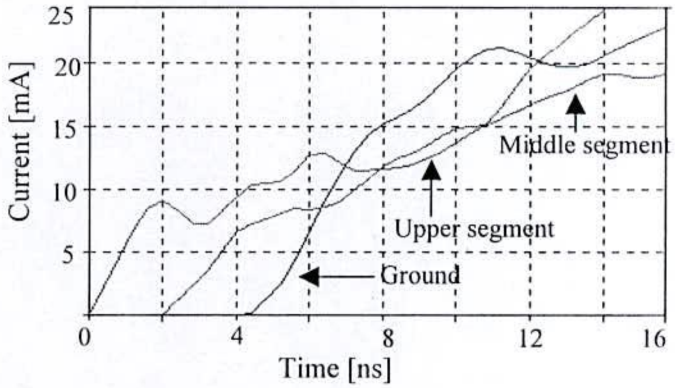


Fig. 14 Upper and middle segment and ground current of vertical conductor. (voltage applied vertically at the lower segment of the channel, channel length- 3.3 m and voltage measuring wire 5.3 m.

From the current wave-shape of the figure any one can analyze the input current, ground current and branch current. Also the current wave shape shown the rising time , delay time and reflection time. Here in the Figs. 13a, 13b, 13c, 13d and 13e and 14 shows 1st curve is for input current, 2nd is for segment current and the 3rd is for ground current. Figs. 13a, 13e and 14 are almost the same for the input current for rising characteristics. There is no delay time in these wave-shape to increase the current and the reflection time is almost 10 ns. Figs. 13b, 13c and 13d are shown some of delay time due to modify the current channel wire and voltage measuring wire. By modifying Fig. 5, current channel is 6 m long and voltage measuring wire is 4 m of long instead of 2 m and in the Fig. 8, voltage measuring wire is 5 m long. Again the middle segment current (2nd curve) of the following wave shape is shown the exact delay time , rising time and the reflection time, same is the calculated time.

4.7 Effect of the Voltage and Current of Single Vertical Conductor by changing the frequency of Line Constant Program (Current Analysis)

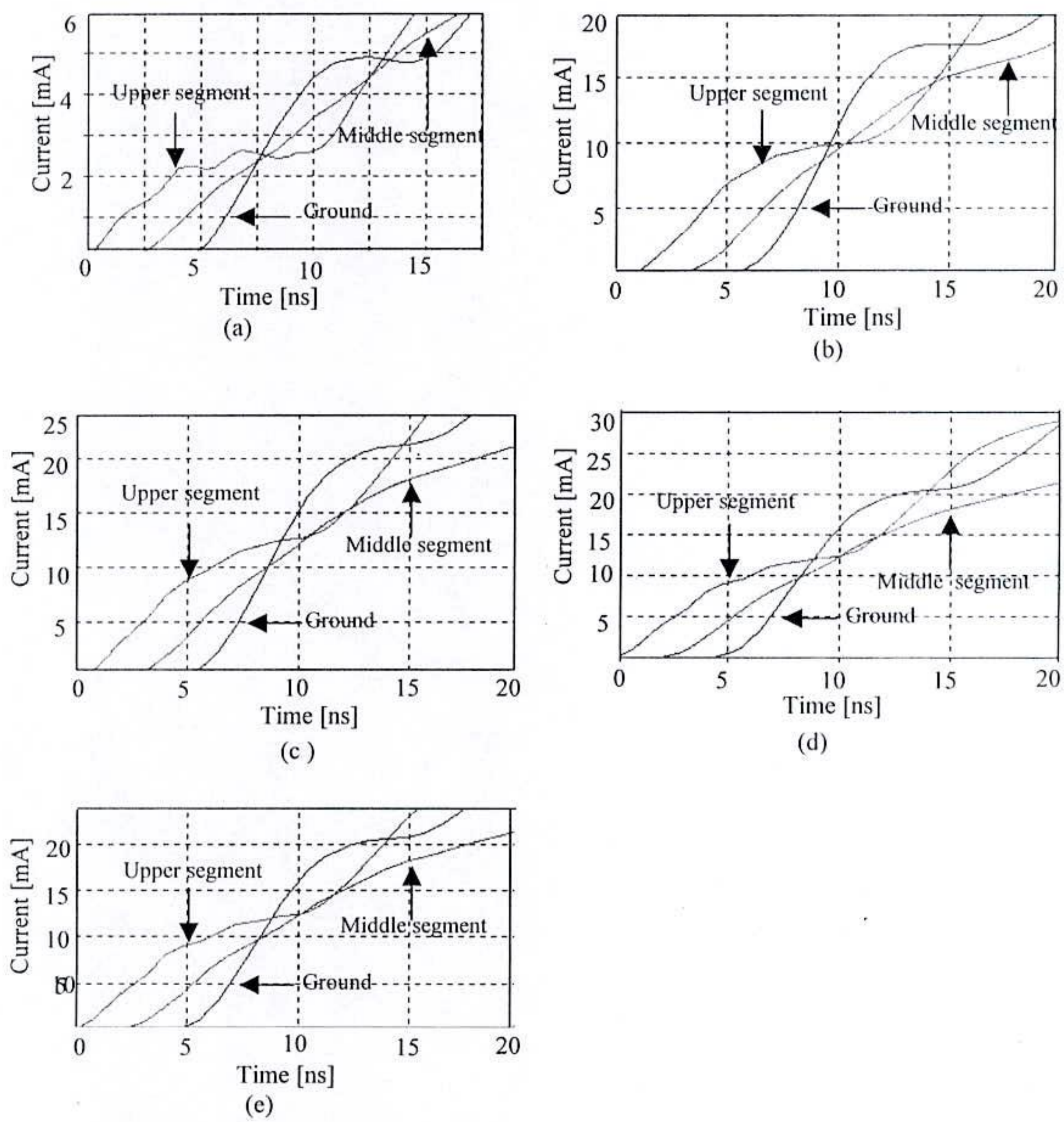


Fig. 15 Current wave shape of different frequency of line constant program. (a) f= 50 Hz, (b) 1000 Hz, (c) f = 0.953×10^6 Hz, (d) f = 3.906×10^6 Hz (e) f = 7.81×10^6 Hz.

In this work ,there exists some effect in the vertical conductor for changing the frequency in the line constant program. To investigate, here is taken different frequencies in the line constant program to see the variation of the voltage and current analysis. In this research five frequencies are taken in the line constant program such as f =50 Hz, 1000 Hz, 0.953×10^6 Hz, 3.906×10^6 Hz and 7.81×10^6 Hz. In the Fig. 15 a, b, c, d and e are shown the current wave-shape characteristics consecutively the reflection time , delay time and the peak value 2.7 mA is at 7.4 ns. In the figure 1st curve is for upper segment current, 2nd is for middle segment current and 3rd is for ground current. In the figure shows as the frequency is increasing in line constant program, the peak value of current is also increasing . It is observed in the Figs. 15a the frequency only 50 Hz and the peak value of the input current is 2.7 mA, where the reflection occurs is 2.5 mA, Fig. 15b the frequency is 1000 Hz and the current is 10 mA and then 12.5 mA for the Fig. 15c, 15d and 15e for the effect of frequency 0.953×10^6 Hz, 3.906×10^6 Hz, 7.81×10^6 Hz respectively. The reflection time of all these figures is approximately 10ns. Only in the Fig. 15b for the frequency 1000 Hz, the reflection time is 11ns. Again for the ground current G01, the current at the reflection time is 4.6 mA, 17.3 mA, 21.5 mA, 21.3mA and 21.2 mA for the above frequencies respectively. That is, in respect of frequency increasing in the line constant program the reflection current is also increasing at the certain time and then decreases very slow. Besides this there are some delay for ground and segment current. 3 ns for segment, 5.9 ns for ground, which is approximately, equals to the calculated value 3.3 ns and 6.6 ns.

Voltage Analysis:

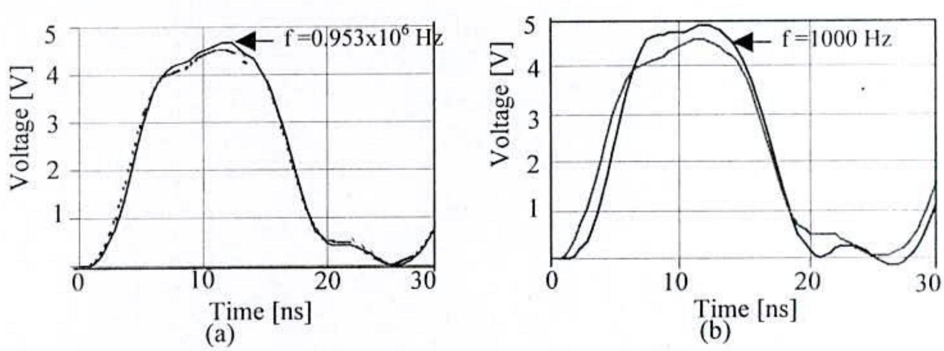


Fig. 16 Voltage Wave-Shape for different frequency of line constant program (a) f= 0.953×10^6 Hz and 7.81×10^6 Hz, (b) f = 1000 Hz and 3.9×10^6 Hz .

It is observed in the Fig. 16 that the comparison of the characteristics of the voltage wave-shape of different frequencies of the line constant program. Here the voltage wave-shape shows that the peak value of the voltage at 12 ns which is approximately equals to the calculated value 13 ns. But the important thing is the frequency variation, at the lowest frequency (50 Hz) in the line constant program which is not in the figure , the peak voltage is maximum, then the it goes to at 4.8V at the frequency 1000 Hz of line constant program. Then again decreases the voltage in to 4.67 V and 4.58 V with the increase of frequency. So by changing the frequency of the line constant program sweetable tower model can be design.

4.8 Voltage Analysis of Single Vertical Conductor With Horizontal Injection varying Current Lead Wire and Voltage Measuring Wire.

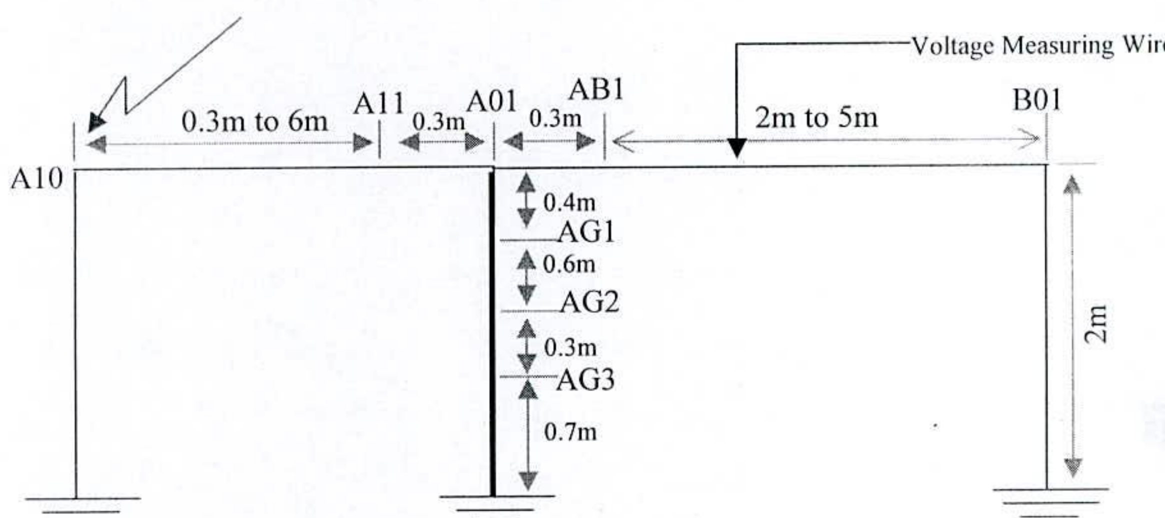


Fig. 17 Horizontally applied Voltage of Vertical Conductor (With Ground).

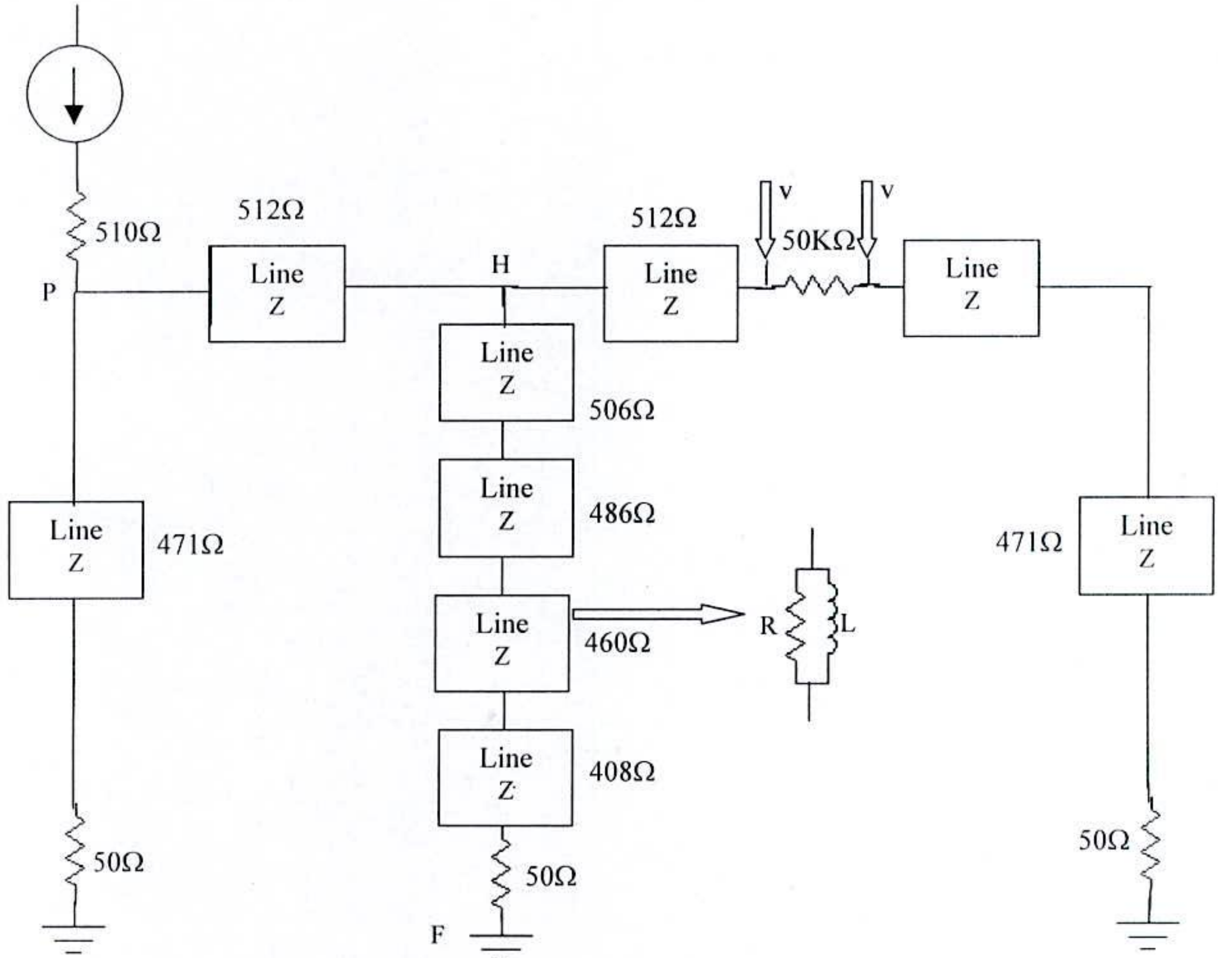


Fig. 18 Equivalent Circuit of Vertical Conductor (With ground).

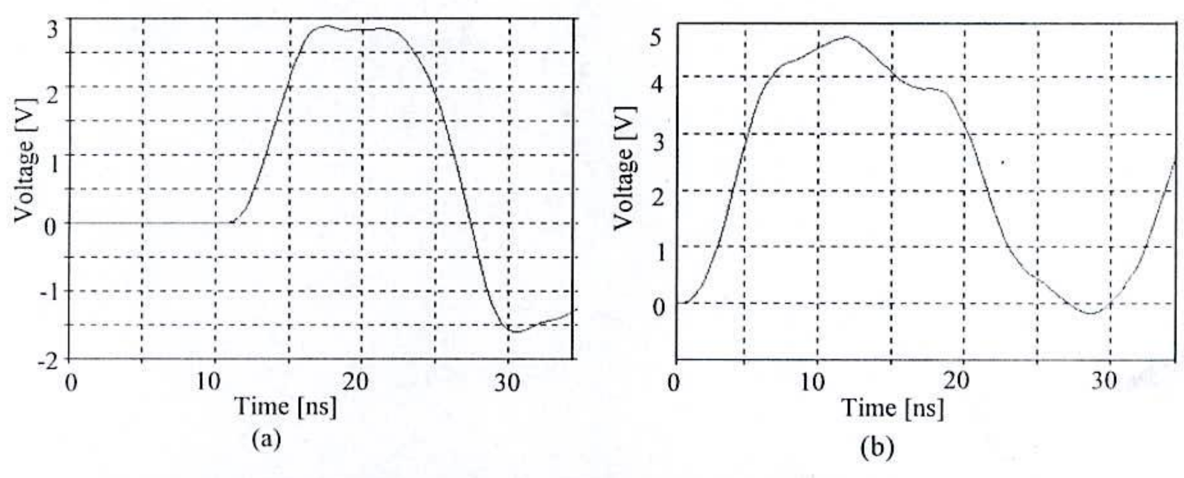


Fig. 19 (**a**) Simulated voltage of vertical conductor. (voltage applied horizontally at the edge of the channel, channel length- 3.3 m and voltage measuring wire-4.3 m, (**b**) Simulated voltage of same model, (voltage applied horizontally at the edge of the channel, channel length- 0.3 m and voltage measuring wire-5.3 m.

In the above voltage wave shape are shown only for two modified model, that is in the model of Fig. 5 voltage measuring wire increased to 4 m and the model of Fig. 17 voltage measuring wire increased to 5 m instead of 2.3 m and the Current channel wire reduced to 0.3 m instead of 3.3 m. In this model voltage is applied horizontally instead of vertically.

So that, from the above voltage waveform of simulation voltage of Fig. 19a and 19b are shown that voltage rises at 11ns and 2 ns , after increasing the voltage wave it reaches at the peak and then fall at downward after 11 ns or 12 ns which indicates approximately equal to the calculated value 13 ns. Fig. 19a shows the delay time for long current lead wire but for the Fig. 19b there is very small time delay for very short current lead wire. Again Fig. 11c and Fig 19 are almost same though one is voltage applied vertically and later is voltage applied horizontally. But only the difference in the Fig. 19a, voltage rises up to 2.9 V of horizontally applied voltage and in the Fig. 11c voltage rises up to 2.6 V of vertically applied voltage. Again in the Fig. 11d and Fig. 19b voltage waveform is almost same in rising time and peak voltage. So the measurement of both of the models for voltage measuring wire 4.3 m and 5.3 m are good for designing in reduced scale model.

4.9 Current Analysis of Single Vertical Conductor of Horizontal Injection, Varying Current Lead Wire and Voltage Measuring Wire

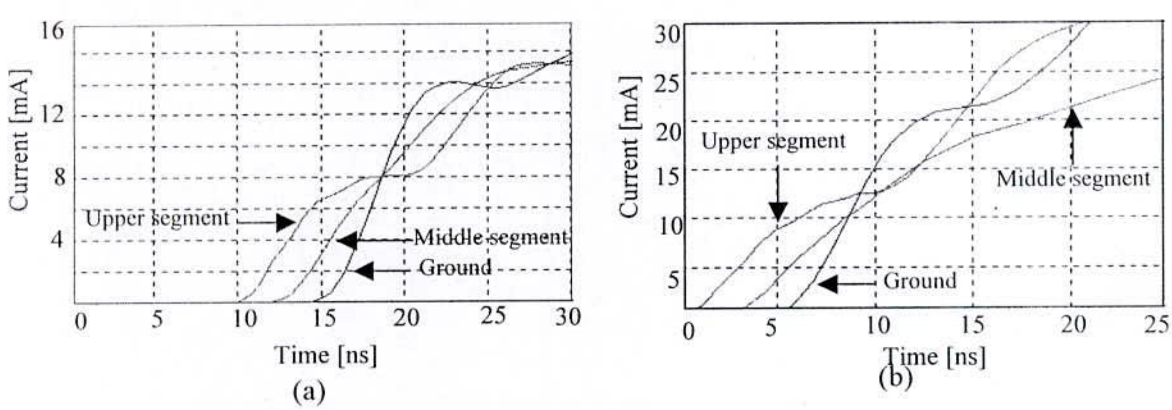


Fig. 20 Upper and middle segment and ground current of vertical conductor of horizontal Injection (a) Current lead wire : 3.3 m and voltage measuring wire : 4.3 m, (b) Current lead wire : 0.3 m and voltage measuring wire : 5.3 m.

From the current wave-shape of the above figure it is shown that the characteristics of input current, ground current and branch current. Also the current wave shape shown the rising time , delay time and reflection time. Here in the Fig. 20a and 20b shows 1st curve is the upper segment current, 2nd curve is for middle segment current and 3rd curve is for ground current. These wave-shapes are almost the same of the Fig. 13d and 13e for rising time , delay time and reflection time. That is for the vertically and horizontally applied voltage for the vertical conductor, the characteristics of the wave-shape are very little difference. In the Fig. 20a there are some delay time for all the current as because the current lead wire is longer for the first wave-shape than the second wave-shape. It is shown in the Fig. 20a the current lead wire is for 3.3 m long and for the Fig. 20b, it is only for 0.3m in length. So the delay time is not same for two cases, 10 ns for 3.3 m current lead wire and 1.5 ns is for 0.3 m length. From the rising time to reflection time for the two wave-shape are almost 10 ns which is approximately equal to the calculate value.
The peak value of the ground current of the Fig. 20a is at 26 ns and the Fig. 20b is at 16 ns, which is almost same for the calculated value . So this is almost appropriate for reduced scale model of vertical conductor.

4.10 Influence of the Ground effect of Current Lead Wire

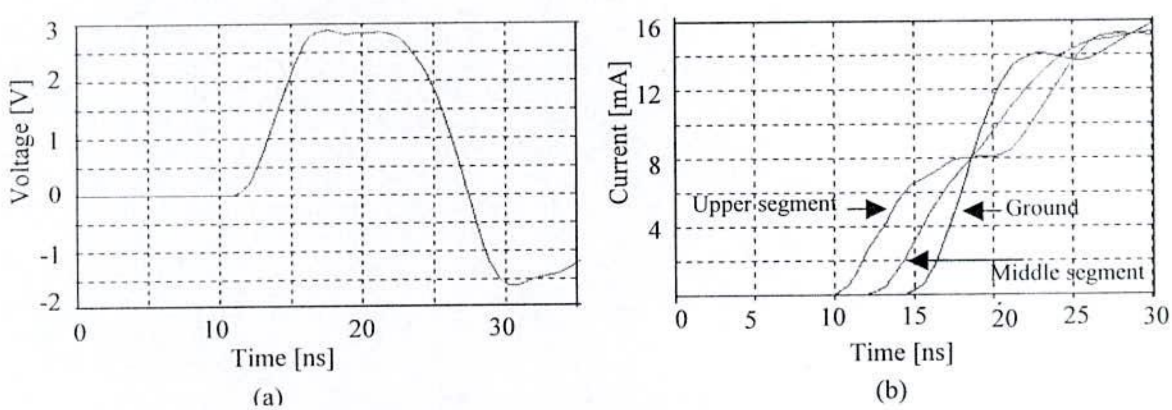


Fig. 21 (a) Simulation voltage of horizontally applied voltage (with Ground),
(b) Upper segment, middle segment and Ground current (with ground).

In this section the model shows that the vertical conductor of horizontally applied voltage, grounded with current lead wire. It has already been discussed for the horizontally applied voltage of vertical conductor but here the characteristics of wave-shape are discussed with grounding the current lead wire. In the Fig. 21a the voltage waveform of the vertical conductor and the Fig. 21b shows the current waveform of the vertical conductor. From the figure it is very clear to see the effect of ground of vertical conductor. It is almost same the delay time, reflection time and the peak value of the current and voltage with the comparison of without ground the current lead wire. In this research, it is seen that there are very little bit difference in the wave-shape for grounding the current lead wire. In the voltage wave-shape the delay time is 11 ns which is almost same for the calculated value and reflection time is 12 ns to 13 ns is just like the calculated value. And in the current wave-shape, the delay time is 10 ns for the input current and the reflection time is also 10 ns for both grounding and non-grounding purpose. So for grounding the current lead wire in the model, there is no major change in the characteristics of voltage and current wave-shape.

4.11 Surge Impedance analysis of Single Vertical Conductor

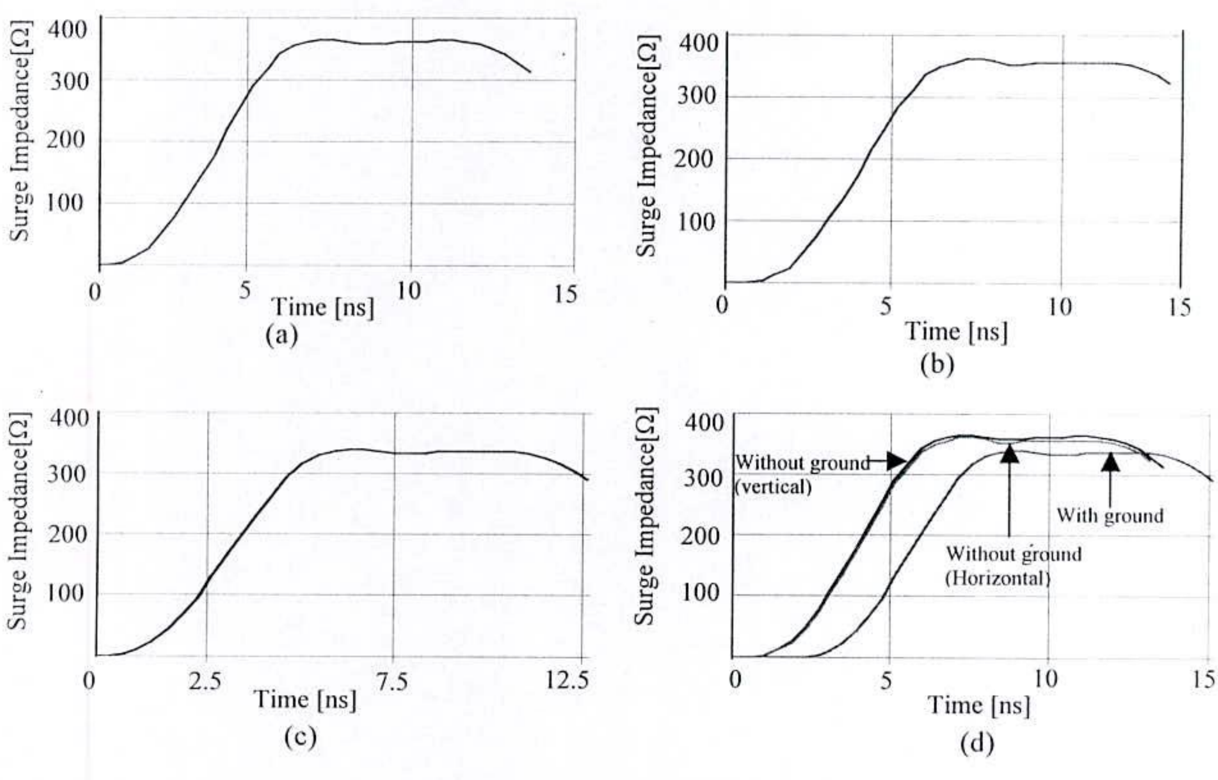


Fig. 22 Surge impedance (**a**) Surge impedance for vertical injection (without ground), (**b**) Surge impedance for horizontal injection (not terminated) , (**c**) Surge impedance for horizontal injection (with ground) , (**d**) Comparison of surge impedance of vertical and horizontal injection .

It is observed in the Figs. 11c, 13d and 21a, 21b that the simulation results of voltages and currents with existence of ground plane and without ground plane by the EMTP analysis for an equivalent circuit representation of Figs. 6 and 18. The starting time of current flowing through the vertical conductor depends on the location of the current injection in the current lead wire. As the pulse is injected at 6 m from the vertical conductor with ground plane as in Fig. 5, the currents start flowing through it after 10 ns from starting current without ground plane case. The occurrence of the reflection can also be observed in Figs. 6 and 21b.

Now Figs. 22a, 22b and 22c shows the simulation results of surge impedance of vertically, horizontally and horizontally with ground effect by the EMTP. Finally Fig. 22d shows the comparison statement of surge impedance using EMTP.

Again by changing the frequency of line constant program there are also greater effect in surge impedance which is shown in Fig. 23 and summarized at Table 3. By using very low frequency surge impedance is very high and increasing the frequency surge impedance decreases which shows in the Fig. 23.

Table : 2 Surge impedances of the vertical conductor at $t \approx 2h/c$.

Surge Impedance	Vertical Stroke	Horizontal Stroke	Horizontal Stroke (Ground Effect)
EMTP Simulation	385Ω	375Ω	350Ω
Theoretical	439Ω	------	411Ω

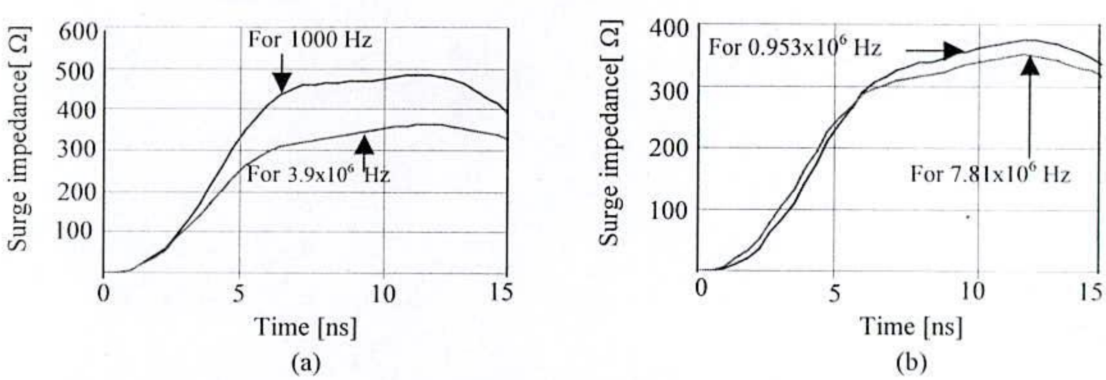


Fig. 23 Surge impedance for different frequency of line constant program (a) For 1000 Hz and 3.9×10^6 Hz, (b) For 0.953×10^6 Hz and 7.81×10^6 Hz .

Table: 3 Surge impedances of the vertical conductor for different frequency at $t \approx 2h/c$.

	50 Hz	1000 Hz	0.953×10^6 Hz	3.906×10^6 Hz	7.81×10^6 Hz
Surge Impedance	1709Ω	485Ω	374Ω	364Ω	350Ω

Theoretical [25][26] and computed by EMTP results can be summarized in the Table: 3 at $t = 2h/c$, so as to make quantitative evaluation. The surge impedance for the ground plane is naturally much lower than that of without ground plane. The theoretical values of surge impedance agree well with the computed values.

4.12 Surge impedance comparison between the system EMTP and NEC-2 (60 cm Vertical Conductor)

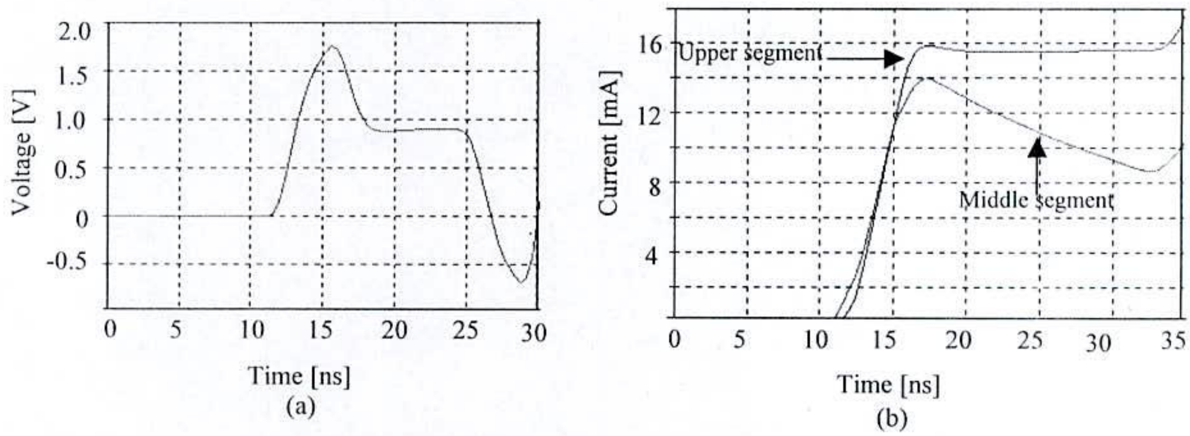


Fig. 24 (a) Simulation voltage for vertical injection, (b) Segment Current .

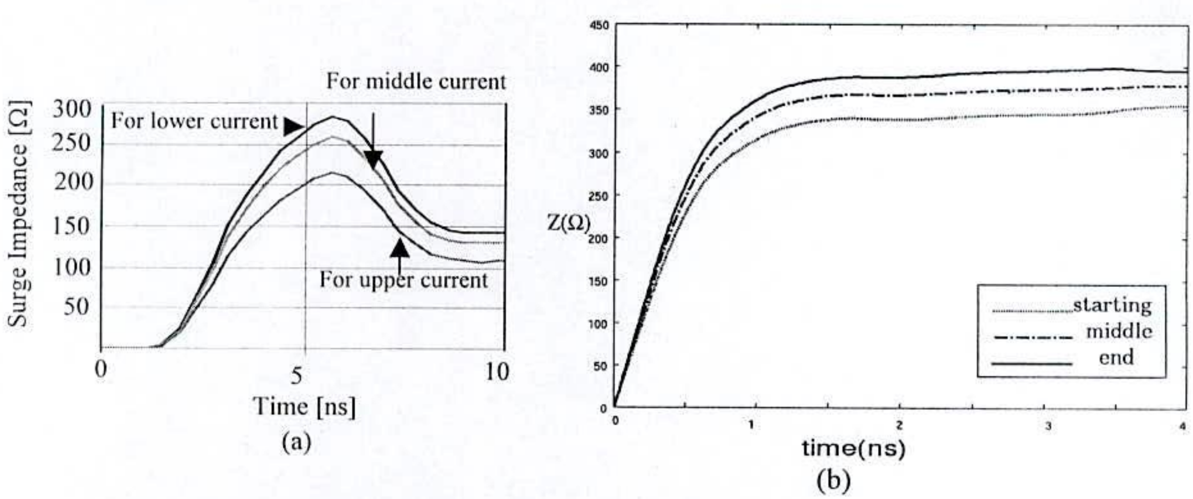


Fig. 25 (a) Surge impedance using EMTP , (b) Surge impedance using NEC-2.

Table : 4 Surge Impedance Comparison

Surge Impedance	Lower Current	Middle current	Upper Current
EMTP	284 Ω	258 Ω	214 Ω
NEC-2	350 Ω	310 Ω	280 Ω
Theoretical	367 Ω	----	----

4.13 Summary

The theoretical values of surge impedances calculated from the theoretical formulas [25][26] are verified by comparing the theoretical and simulation results on simple structures. The difference is less than about 18 to 20% at time $t = 2h/c$, which is within the accuracy maintained in the analysis. Results measured on reduced-scale models, therefore, have hardly been employed in the practical calculation of the lightning phenomenon and electromagnetic behavior of a three dimensional system struck by lighting. Also, the traveling wave propagating at nearly the velocity of light is observed here. The surge characteristics have some influence on the type of the lighting current with the presence of ground plane and without the ground plane. The difference between the theoretical waveforms and computed waveforms comes naturally from the different electromagnetic field around the vertical conductor influenced mainly by the electric fields associated with the currents propagating the vertical conductor and current lead wire. Again frequency of line constant program is also greater effect in surge analysis in single vertical conductor. From the comparison statement table it is shown that changing the frequency of line constant program there exists greater effect in surge impedance on single conductor. From the table-3 it is shown that surge impedance is inversely proportional to the frequency of the line constant program. Again surge impedance of 0.6 m vertical conductor using EMTP is shown in the table–4 with comparison statement with NEC-2 and theoretical value. Surge impedance using EMTP is 18% less than NEC-2 and 22% less than theoretical value.

Chapter # 5

Base-broadened Tower

5. Four Pole (Base-broadened) Conductor

5.1 Introduction

In the Fig. 26 shows the four pole conductor or base-broadened tower of reduced scale model. Here the tower is taken 4m long as a model of the actual tower and it is divided into seven segments from bottom to the top of the tower, each of 0.5 m in length except the bottom segment is 1 m in length. Each segment of the tower is of different in diameter as in the Fig. 26b.

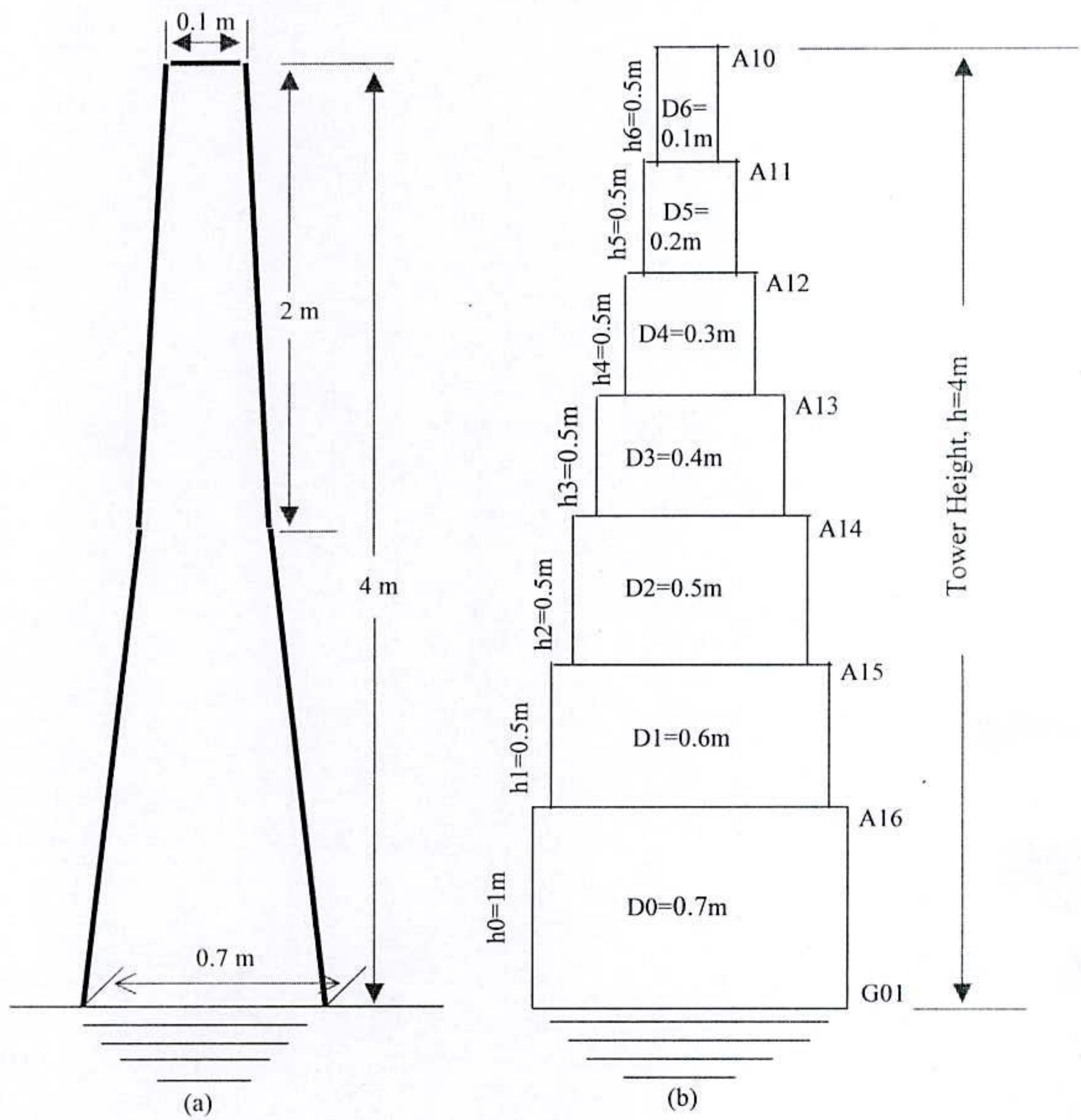


Fig. 26 Base-broadened four pole Conductor (a) Main Pole, (b) Segment of the pole.

The voltage measuring wire of the arrangement of Fig. 27 is taken 10 m in length and the current lead wire is 6 m in length and the voltage is applied vertically at the top of the base-broadened tower. In this section surge impedance is simulated both vertical and horizontal injection and their comparison is investigated.

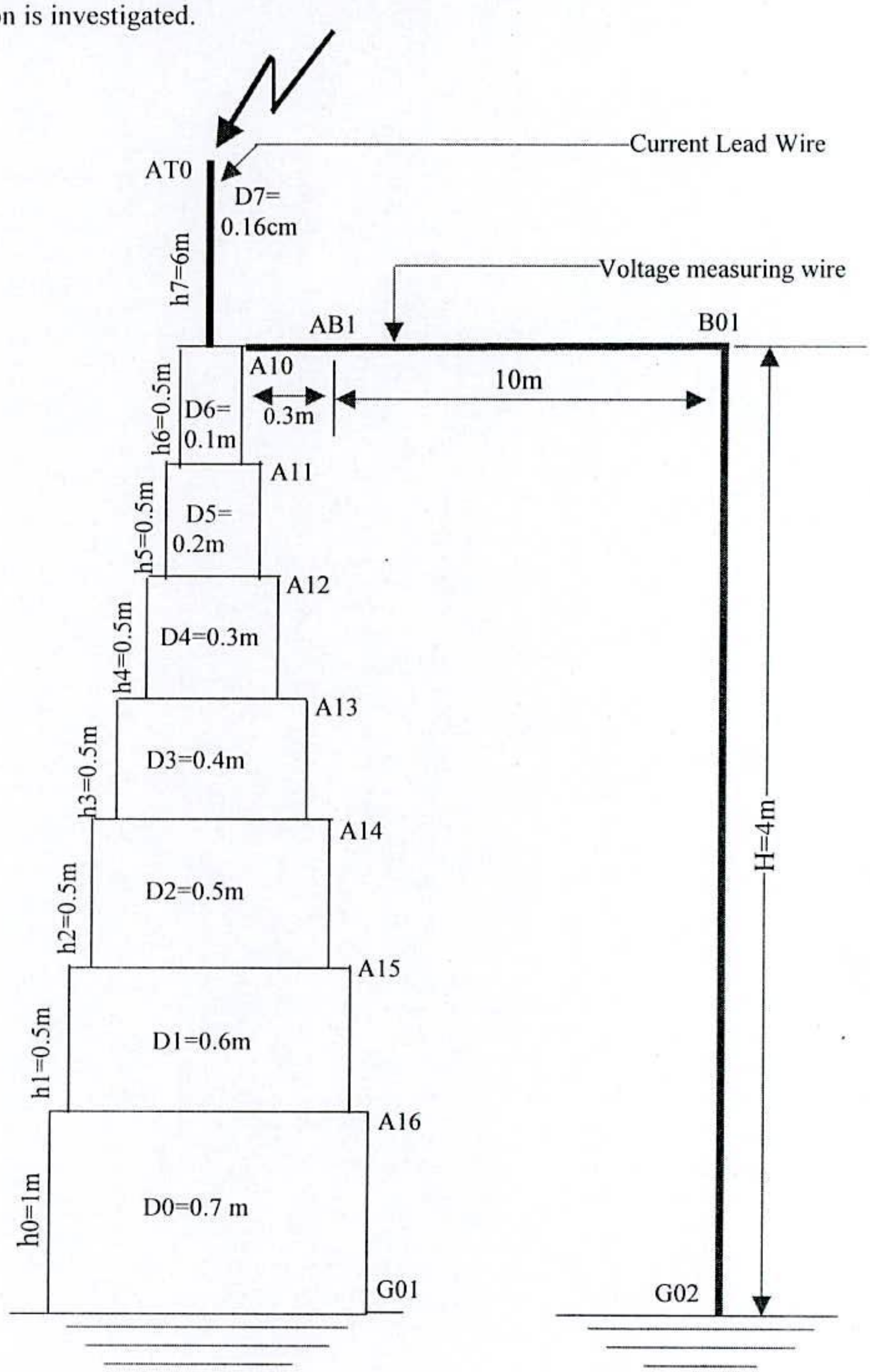


Fig. 27 Arrangement of the voltage measuring wire and current lead wire of the tower.

5.2 Voltage analysis of Base-broadened four Pole Conductors with Vertical Injection

Here the simulation is carried out using two combinations for four pole vertical tower, they are: i) Vertically applied voltage at the top of the current lead wire ii) Horizontally applied voltage at the edge of the channel. In this section voltage is analyzed in the Fig. 28 by applying vertical injection at the top of the channel shown in the Fig. 27 .

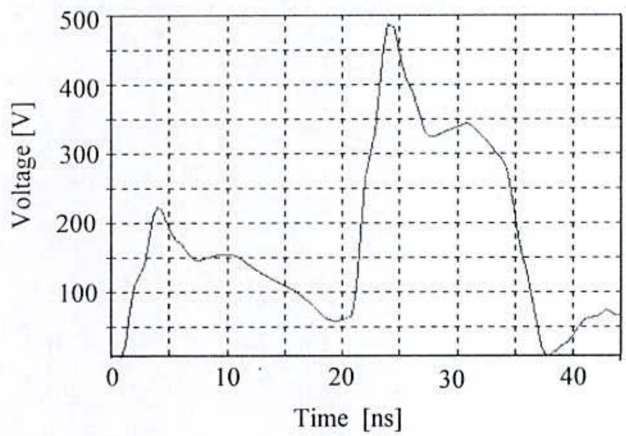


Fig. 28 Simulation Voltage of the Tower for vertical injection.

From the combinations of the model, it is shown in the Fig. 27 and Fig. 31 that voltage is applied vertically at the top of the current channel and the voltage is applied horizontally of the current channel. Fig. 28 voltage-wave shows the characteristics of the base-broadened tower. 50 ns is taken for one complete pulse-width and 1 kV is for applied voltage. There exists small delay time in the voltage waveform before the beginning of rising point. The delay time is 1 ns and the pulse of the voltage wave-shape is approximately 35 ns.

So that from the above voltage waveform is shown that voltage rises at 1 ns and fall at 24.ns, the falling time should be at 26 ns. That is if the surge current propagates along the tower at the speed of light, the reflected wave from the ground should return to the tower top after twice of the tower travel time which is 26 ns for the structure of the model in the Fig. 27.
That means a negative voltage wave is induced at the tower foot before the occurrence of the reflection of the voltage wave propagating down from the tower top and is is almost the same to the calculated value. So by simulation from the above voltage waveform in the Fig. 28 is correct to design the reduced scale model.

5.3 Current analysis of Base-broadened four Pole Conductor with Vertical Injection

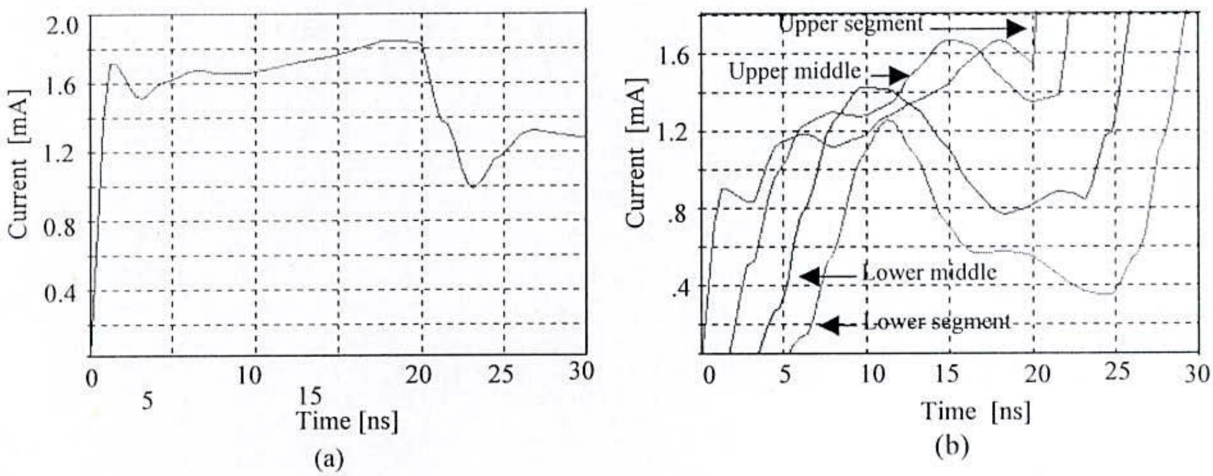


Fig. 29 (a) Injected Current, (b) Upper segment, middle segment and lower segment current of the tower.

From the current wave-shape of the above Fig. 29a and 29b shows the characteristics of injected and segment current respectively. The current wave shape shows the rising time, delay time and the reflection time. In the Fig. 29a shows the input current and in the Fig. 29b shows four segments current. Each segment current have some delay time for some short length 0.5m and the reflection time of each segment current are 6 ns. In Fig. 29a shows the input current and its reflection time is 23 ns which is exactly the same for simulation value. The pulse width of the injected current is 23 ns, which is approximately to the calculated value. In the Fig. 29b shows the segment current, 1st curve is for the upper segment, 2nd and 3rd for the middle segment current and 4th curve is for the lower segment current, each of the current have some delay time for some length, rise time and reflection time as discussed in the previous chapter.

5.4 Surge Impedance analysis of Base-broadened four Pole Conductors with Vertical Injection

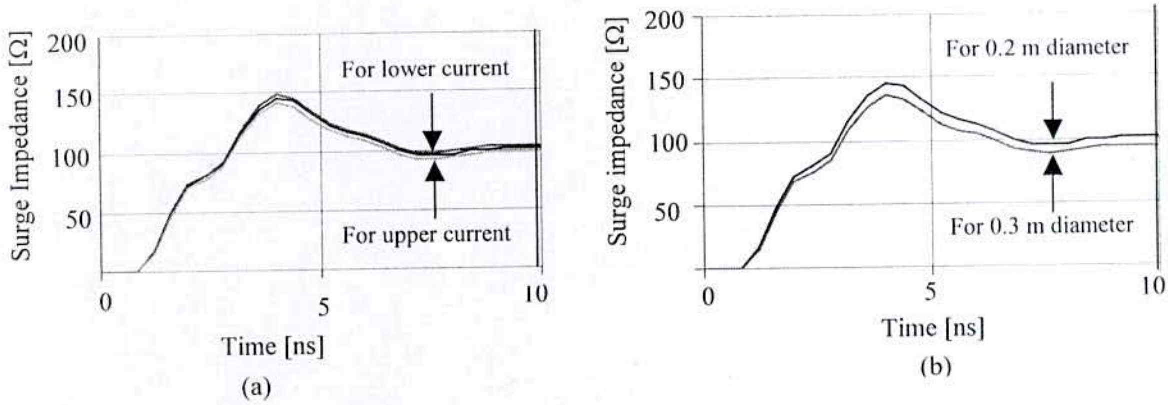


Fig. 30 Surge impedance (a) For vertical injection, (b) For different diameters.

Here in the above Figs. 30a and 30b shows the surge impedance curve of base-broadened four pole conductor for vertically applied voltage. In the Fig. 30a shows three curves for surge impedance of upper, middle and lower of the tower 1st segment current. The maximum surge impedance 148 Ω is for the minimum of the input current of the tower model, the 2nd curve is for middle current, the surge impedance is 145 Ω and 141 Ω for upper current. All the three surge impedance are close to the theoretical value.

Again in the Fig. 30b shows two curves for surge impedance for two diameter, upper value is 145 Ω for 0.2 m diameter and lower value is 135 Ω for 0.3 m, which can compare the surge impedance for different diameter. That is surge impedance is decreasing for increasing the diameter of the conductor. The tower surge impedance decreases approximately 7% by increasing diameter. It is known that the radius of the main pole has some influence on the tower surge impedance, which might be difficult to take account of in using an analytical formula for the evaluation of the tower surge impedance.

5.5 Voltage Analysis of Base-broadened four Pole Conductor with Horizontal Injection

In the Fig. 31 shows the four pole or base-broadened tower of reduced scale model as like as in the Fig. 26 except the voltage applying position is different. Here voltage is applied horizontally instead of vertically. Length and diameter of the tower is almost same as in the Fig. 26.

In the following Fig. 32a shows the voltage curve for four-pole conductor of horizontally applied voltage of the tower. This model is all the same only the difference is voltage is applied horizontally instead of vertically. Fig. 32a voltage-wave shows the characteristics of the base-broadened tower. 50 ns is taken for one complete pulse-width and 1 kV is applied for surge voltage, small delay time in the voltage waveform before the beginning of rising point. The delay time is 1 ns and the pulse of the voltage wave-shape is approximately 37 ns.
So that from the following voltage waveform of Fig. 32a is shown that voltage rises at 1 ns and start falling at 23.ns, the falling time should be at 26 ns. Now if the surge current propagates along the tower at the speed of light, the reflected wave from the ground should return to the tower top after twice of the tower travel time, which is 26 ns for the structure of the tower model.

that is the calculated value is almost the same of the simulation value which shows in the Fig. 32a. So it is easy to compare the characteristics of the voltage wave-shape of base-broadened four pole conductor of vertically applied voltage Fig. 28 and horizontally applied voltage Fig. 32a.

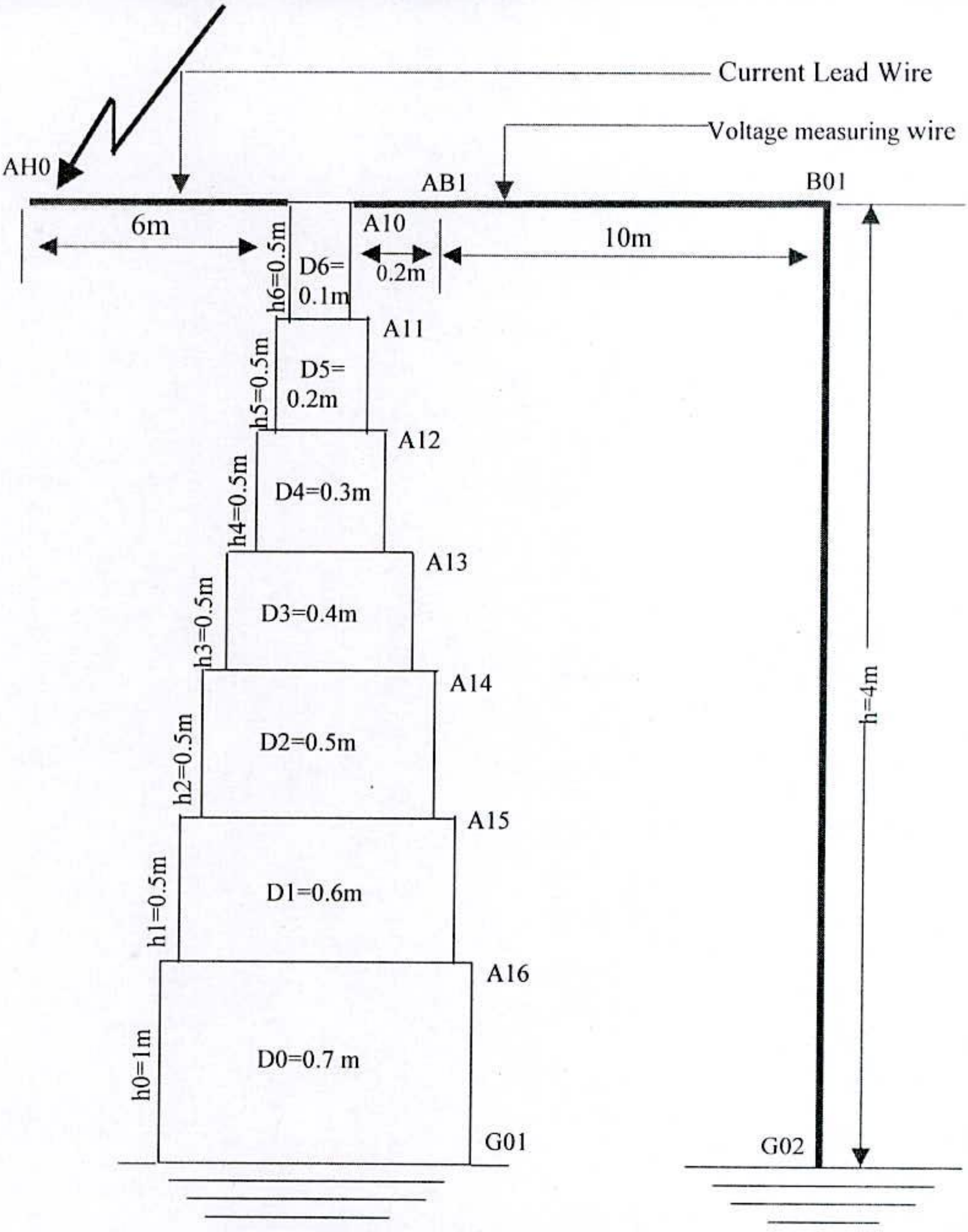


Fig. 31 Arrangement for Horizontally applied voltage of the Tower.

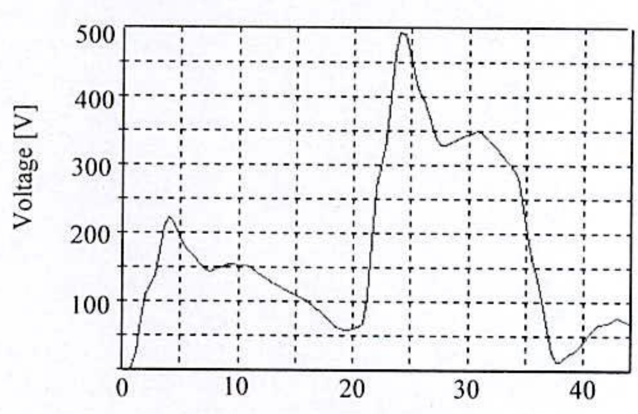


Fig. 32 Simulation voltage for horizontal injection.

5.6 Current Analysis of Base-broadened four Pole Conductors with Horizontal Injection

From the current wave-shape of the above Fig. 33a and 33b shows the characteristics of input and injected current and segment current respectively. Also the current wave shape shown the rising time, delay time and reflection time. Here in the figure shows input and injected rises at 1ns, which is taken in the input value. The reflection time occurs at 23 ns for both input and injected current, which is shown in the Fig. 33a.

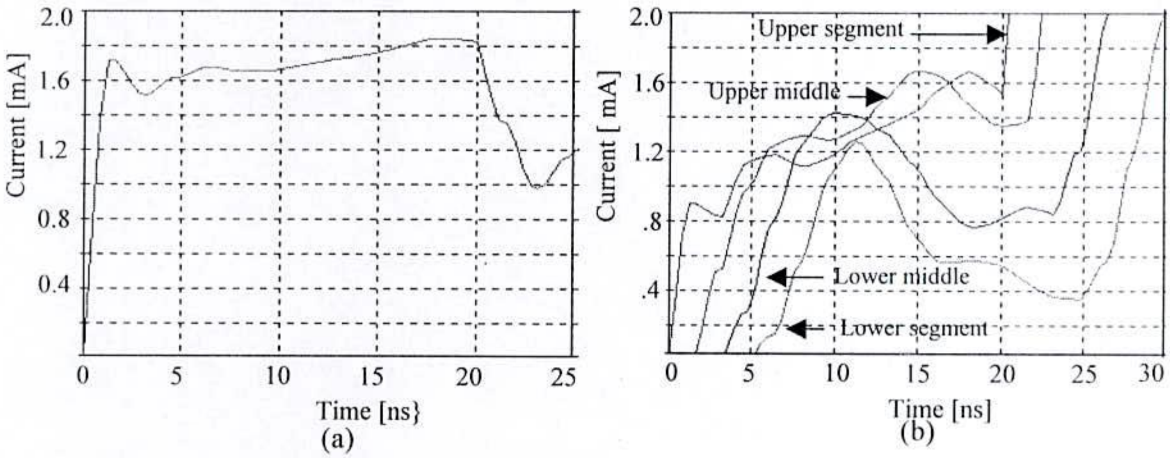


Fig. 33 (a) Injected current of the tower, (b) Upper segment, middle segment and lower segment current.

In the Fig. 33b shows the four segments current of the vertical tower. Each segment current have some delay time for some short length 0.5 m and rises at the peak value after 20 ns. Again each segment current have some delay time. In the figure shows delay time of 2nd curve is 1.5 ns, 3rd curve is for 2.75 ns and 4th current is for 5.5 ns for different length in vertical tower.

5.7 Surge Impedance analysis of Base-broadened four Pole Conductors with Horizontal Injection

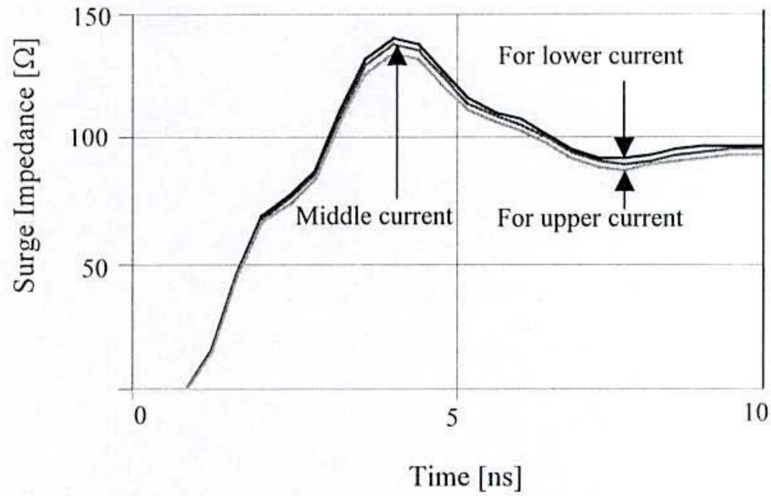


Fig. 34 Surge impedance for horizontal injection.

Here in the above Fig. 34 shows the surge impedance curve of base-broadened four pole conductors for horizontally applied voltage. The figure shows three curves for surge impedance. The maximum surge impedance is for lower current, the surge impedance is 140 Ω and the 2nd curve is for middle current , the surge impedance is 138 Ω and 3rd curve is for upper current, its value is 134 Ω for horizontally applied voltage. But for the reflection current surge impedance is 145 Ω for vertically applied voltage which 5% greater than horizontally applied voltage.

5.8 Comparative Statement for Surge Impedance

Table : 5 Surge Impedance

	For lower current	For middle current	For upper current
Vertical Injection	148 Ω	145 Ω	141Ω
Horizontal Injection	140 Ω	138 Ω	134Ω
Theoretical	------	-------	123Ω

From the comparative statement of the table it is observed that surge impedance of vertical injection is greater than horizontal injection. For vertical injection surge impedance is 148 Ω for lower current, 145 Ω for middle current and 141 Ω for upper current. Again for horizontal injection surge impedance is 140 Ω for lower current, 138 Ω for middle current and 134 Ω for upper current. But the theoretical surge impedance is 123 Ω. So it is very easy to compare the surge between the theoretical value and the simulation value.

5.9 Summary

In this chapter surge impedance is simulated using EMTP for base-broadened tower. Generally base-broadened tower is of different diameter so the surge impedance is also varies for different diameter. The theoretical values of surge impedances calculated from the theoretical formulas [25][26] are verified by comparing the computed on simple structures. The difference is 12% at time $t = 2h/c$ for vertically applied voltage and 8% for horizontally applied voltage, which is within the accuracy maintained in the analysis. Results measured on reduced-scale models, therefore, have hardly been employed in the practical calculation of the lightning phenomenon and electromagnetic behavior of a three dimensional system struck by lighting. Also, the traveling wave propagating at nearly the velocity of light is observed here. Again surge characteristics have some influence for the different diameter of the tower, from the simulation result it is shown that diameter is inversely proportional to the surge impedance.

6 Surge Impedance for Control Building (CB)

6.1 Introduction

The Control Building is called the group of conductors, makes a rectangular form situated above the ground with other conductor. And if the lightning surge hit inside or on the control building then there will be some effect of voltage and the current properties, so the surge impedance should proper for designing a control building. So any one can analyze the transient phenomena such as surge voltage, current , surge impedance, velocity of propagation of the travelling wave and so on. In the following Fig. 35, a simple structure of control building is shown. In the following structure A01-B01, B01-C01, C01-D01 and D01-A01 forms the rectangular structure and each angle is grounded with individual conductor A01-G01, B01-G02, C01-G03 and D01-G03. It is a reduced scale model and the work is done by applying the voltage vertically and horizontally for analyzing the surge characteristics.

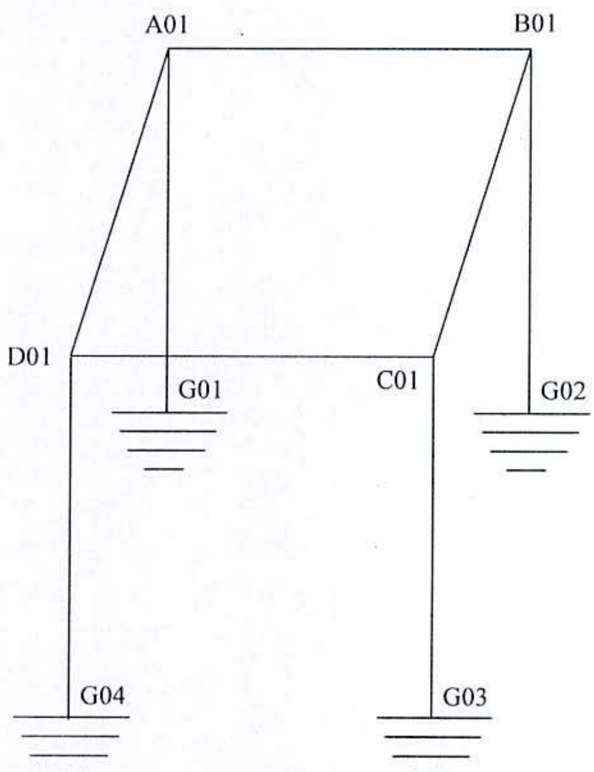


Fig. 35 A simple Structure of Control Building.

The analysis of the control building is done with different system, i.e. by using vertically applied voltage, horizontally applied voltage, different segments of the conductor or without segment of the conductor. Here in the following figures all the systems are discussed one after another.

6.2 Control Building With Vertical Injection (No Segment of the Conductor Leg)

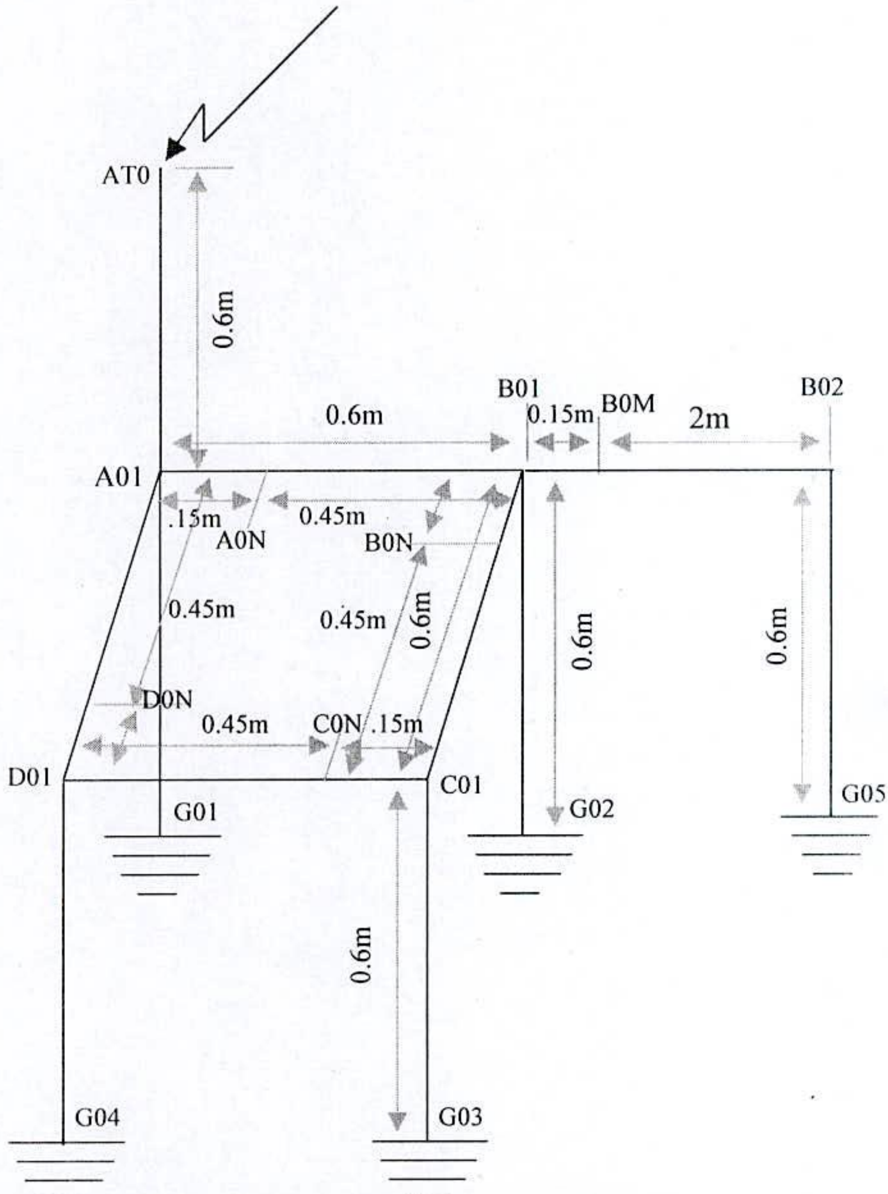


Fig. 36 Control Building-1 with vertical injection (No Segment of the Conductor Leg)

Figure 36 shows a model of control building which has no segment of the conductor leg but the segment occurs in the conductor which is parallel to the ground. In this model the surge is applied at the top of the vertically extended current lead wire of control building. Now the characteristics of voltage, current and surge impedance is to be determined.

6.2.1 Voltage Analysis of Control Building with Vertical Injection (Without Segment of Conductor)

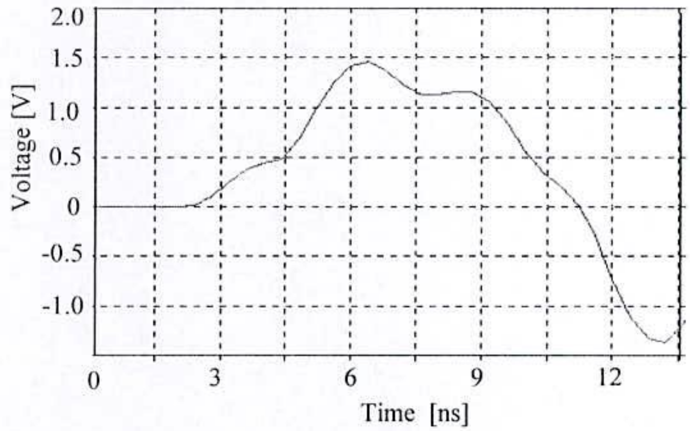


Fig. 37 Simulation voltage .

The characteristics of the voltage wave form of control building with vertically applied voltage shown in the Fig. 37. This model of the control building is analyzed without segment of the conductor leg. 40 ns is taken for one complete pulse-width and 5 V is applied for surge representation. There consists small delay time in the voltage waveform before the beginning of rising point. The delay time is 2.45 ns and the pulse of the voltage wave-shape is approximately 11 ns.

So that from the above voltage waveform of measuring voltage curve of Fig. 37 is shown that voltage rises at 2.45 ns and start falling at 6.45 ns. Now if the surge current propagates along the tower at the speed of light, the reflected wave from the ground should return to the tower top after twice of the tower travel time which is 4 ns for the structure of the model of Fg. 36. So the calculated value is exactly the same of the simulation value which shows in the Fig. 37. So that from the above voltage waveform of simulation voltage curve of Fig. 36a is good in reduced scale model.

6.2.2 Current Analysis of Control Building with Vertical Injection (Without Segment of Conductor)

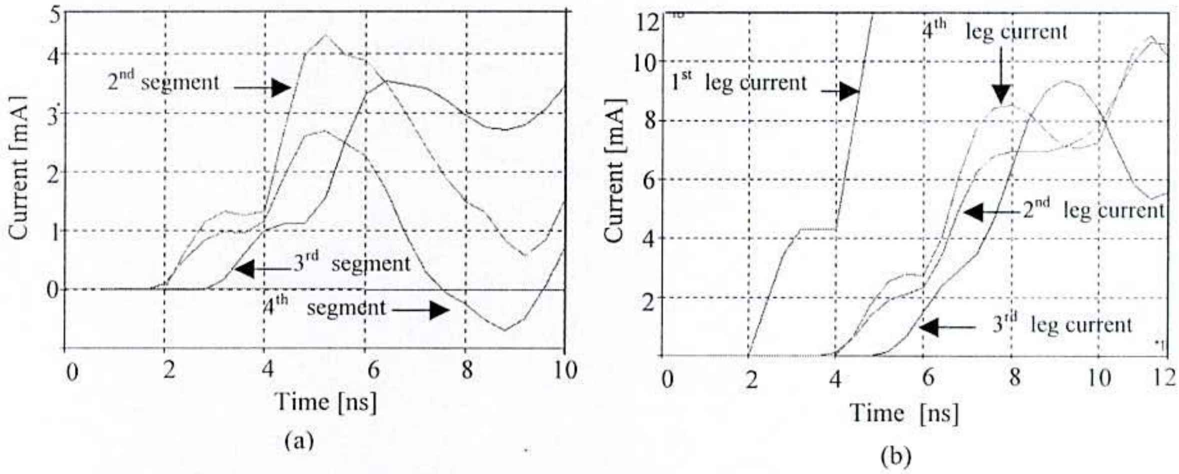


Fig. 38 (a) Segment current of parallel to the ground, (b) Ground current

From the current wave-shape of the Fig. 38a and 38b, they show the characteristics of segment current of the conductors which are parallel to the ground and ground current respectively. Also the current wave shape shown the rising time , delay time and reflection time. In the Fig. 38a shows three segment currents have some delay time for some short length 0.6 m and 1.2 m, the reflection time of each segment current is 7 ns. From the model of Fig. 36 shows current lead wire is 0.6 m and B01 and D01 is the same distance of length 0.6 m from the node A01. So the delay time of the current 1st and 2nd curve in the figure is same 2 ns. Again the node C01 is longer length than the node B01and D01, so the delay time for this current is 3 ns which is almost equal to the calculated value. The rising time of each segment current is 3.2 ns.

Now in the Fig. 38b shows the ground current of each conductor legs have also the delay time, rising time and the reflection time. The ground point G02 and G04 shows in the Fig. 36 is the double distance than the point G01 from the node A01. So the delay time of 1st curve is 2 ns and 2nd and 3rd curve is 4 ns and 4th curve is 5 ns which is almost the same of the calculated value 2 ns, 4 ns and 5 ns respectively.

6.3 Control Building With Vertical Injection (Four Segments of the Conductor Leg)

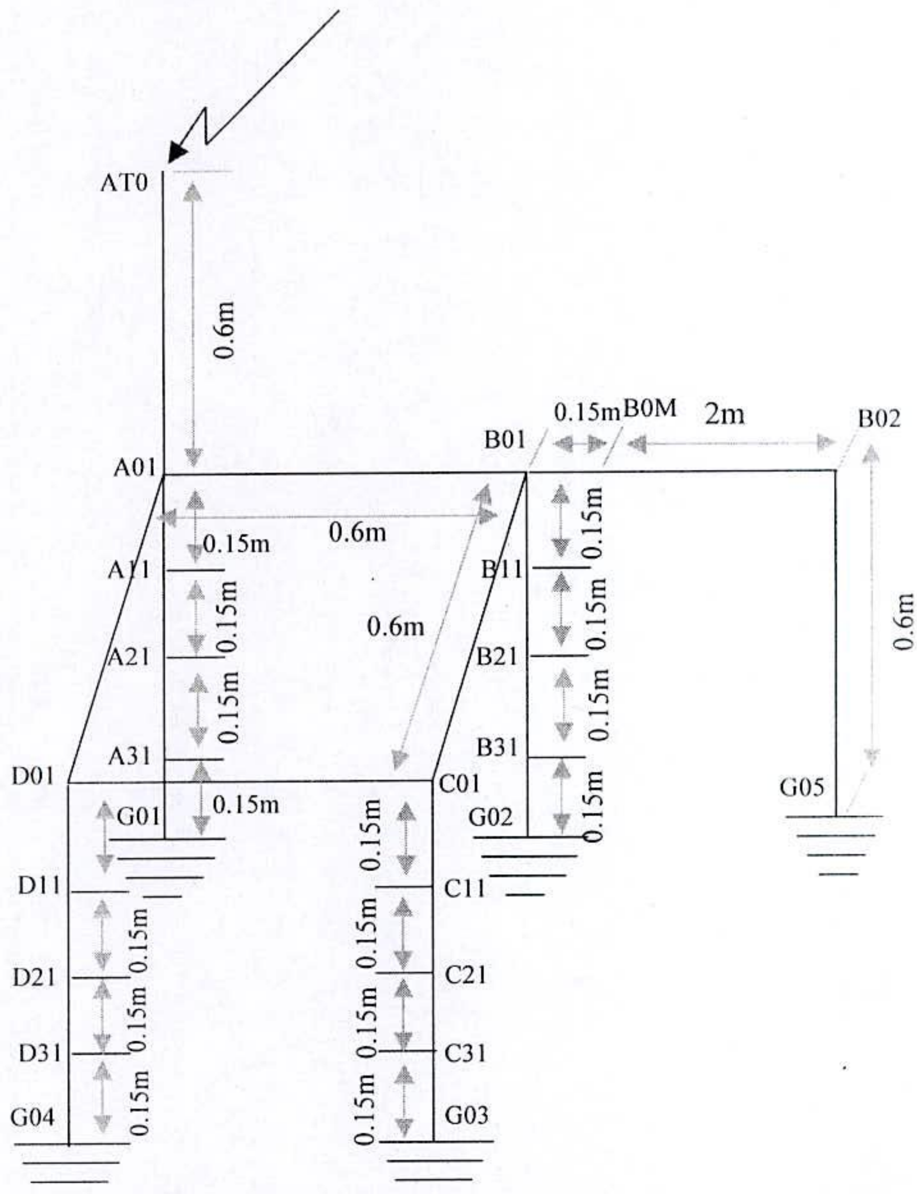


Fig. 39 Control Building-2 with Vertical Injection (Four Segment of the Conductor Leg).

It is shown in the Fig. 39 that a model of control building which have four segments of each conductor leg but no segment occurs in the conductor which is parallel to the ground. In this model the surge is applied at the top of the current lead wire of control building. Now the characteristics of voltage, current and surge impedance is to be determined.

6.3.1 Voltage Analysis of Control Building with Vertical Injection (Four Segments of each Conductor Leg)

Figure 40 voltage-wave shows the characteristics of the control building of vertically applied voltage and each conductor leg is divided into four segments of the control Building. 40 ns is taken for one complete pulse-width and 5V is applied for surge representation. There consists small delay time in the voltage waveform before the beginning of rising point. The delay time is 2.2 ns and the pulse of the voltage wave-shape is approximately 6 ns.

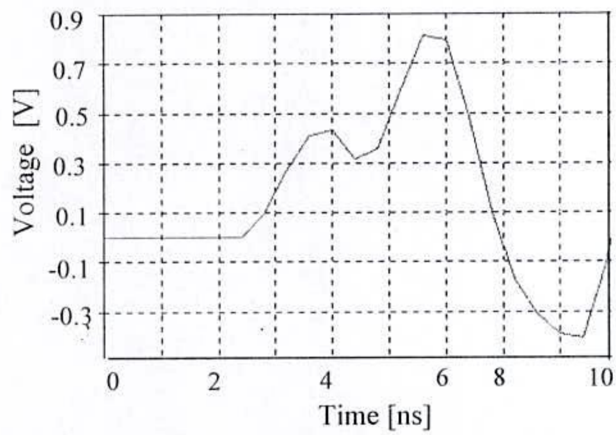


Fig. 40 Simulation voltage of the previous model.

So that from the above voltage waveform of Fig. 40 it is shown that voltage rises at 2.2 ns and start falling at 6 ns. So that the rising time is 3.8 ns. Now if the surge current propagates along the tower at the speed of light, the reflected wave from the ground should return to the tower top after twice of the tower travel time which is 4 ns for the structure of the model of Fig. 39.

6.3.2 Current Analysis of the Control Building with Vertical Injection (Four Segments of each Conductor Leg)

From the current wave-shape of the Figs. 41a, 41b and 41c, shows the characteristics of injected current , upper segment current and ground current respectively. Also the current wave shape shows the rising time , delay time and reflection time. Here in the Fig. 41a shows the injected current and 41b shows the four segment current of each upper conductor part and Fig. 41c shows the ground current of each conductor. Each input current have some delay time and reflection time for some short length.

In Fig. 41b shows 1st curve starts from origin and no delay time, because node A01 in the Fig. 39 is the first point and surge current didn't propagate any distance, on the other hand current of

2^{nd} curve and 3^{rd} curve starts with same delay time 2 ns, as the calculated value, because they propagate same distance and current of 4^{th} curve starts with more delay time 4 ns which is exact to the calculated value 4 ns. The reflection times of all the input current are same 2 ns.

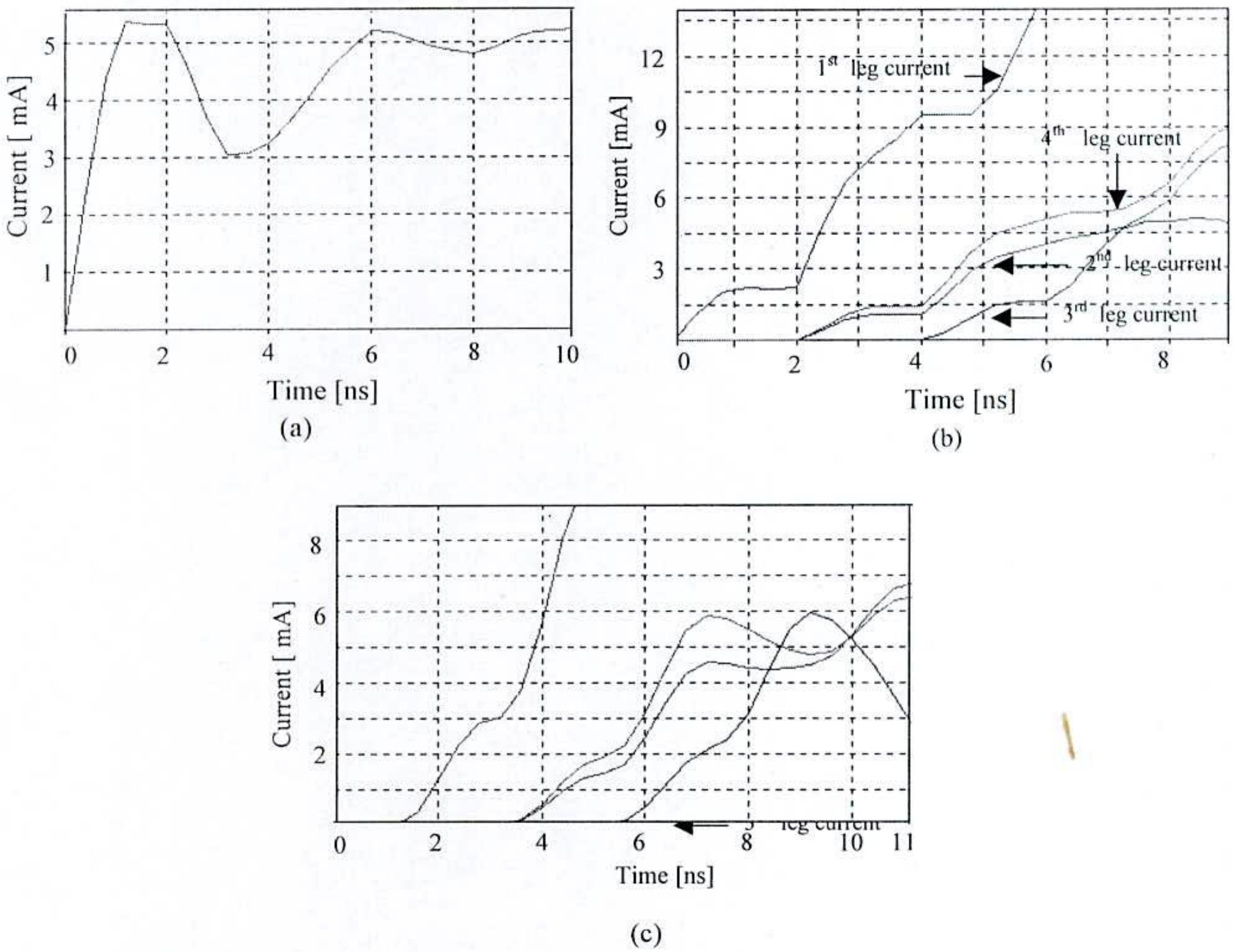
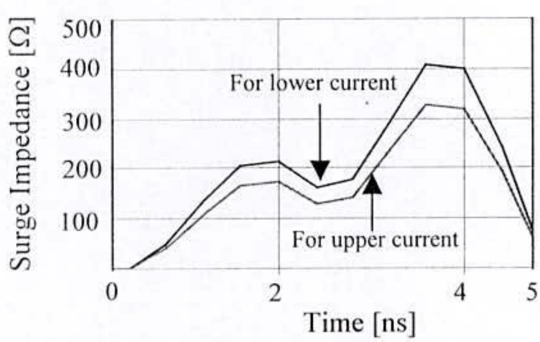


Fig. 41 (a) Injected current of the model, (b) Upper segment current of the four conductor Leg, (c) Ground Current of each conductor of Control Building.

Now Fig. 41c shows all the ground current of each conductor leg have also delay time , reflection time and rise time . In the figure the ground current of 2^{nd} and 3^{rd} curve have the same delay time 3.8 ns for surge current propagates same distance, current of 1^{st} curve is for 1.8 ns and 4^{th} curve is for 5.8 ns. For the 4th current surge current propagates greater length compare to the node G02 and G04. And the simulation rise time of all the ground current is 4 ns which is almost the same of calculated value for surge current propagates 1.2 m of length of travelling and return time of the model shown in Fig. 39

6.3.3 Surge Impedance Measurement of Control Building with Vertical Injection (Four Segments of each Conductor Leg)

The following Fig. 42 it is observed that the surge impedance of control building with vertically applied voltage. The two are the wave-shapes shows in the Fig. 42 for surge impedance. The maximum surge impedance 406 Ω is for the minimum current of the input value of the model of the Fig. 39, the lower surge impedance is for higher current, the surge impedance is 324 Ω. The surge impedance 324 Ω is for minimum value of current where the reflection occurs, so this surge impedance is reliable for the control Building.



406Ω For Lower value of Input Current
324Ω For Upper value of Input Current

Fig 42 Surge Impedance of the control building-2.

6.4 Control Building With Vertical Injection (Four Segments of the Conductor Leg and two segments of each Conductor Parallel to the Ground)

For simulation another model in Fig. 43 shows a control building which have four segments of each conductor leg and two segments of each conductor, which is parallel to the ground. The differences between two models of Fig. 39 and Fig. 43 is, each conductor legs of two models are divided in to four segments but the conductors parallel to the ground are not same format. In this model each conductors parallel to the ground are divided in to two segments but no segment in the model shown in the Fig. 39. In this model the surge is applied at the top of the current lead wire of control building as the previous model. Now the characteristics of voltage, current and surge impedance is to be determined.

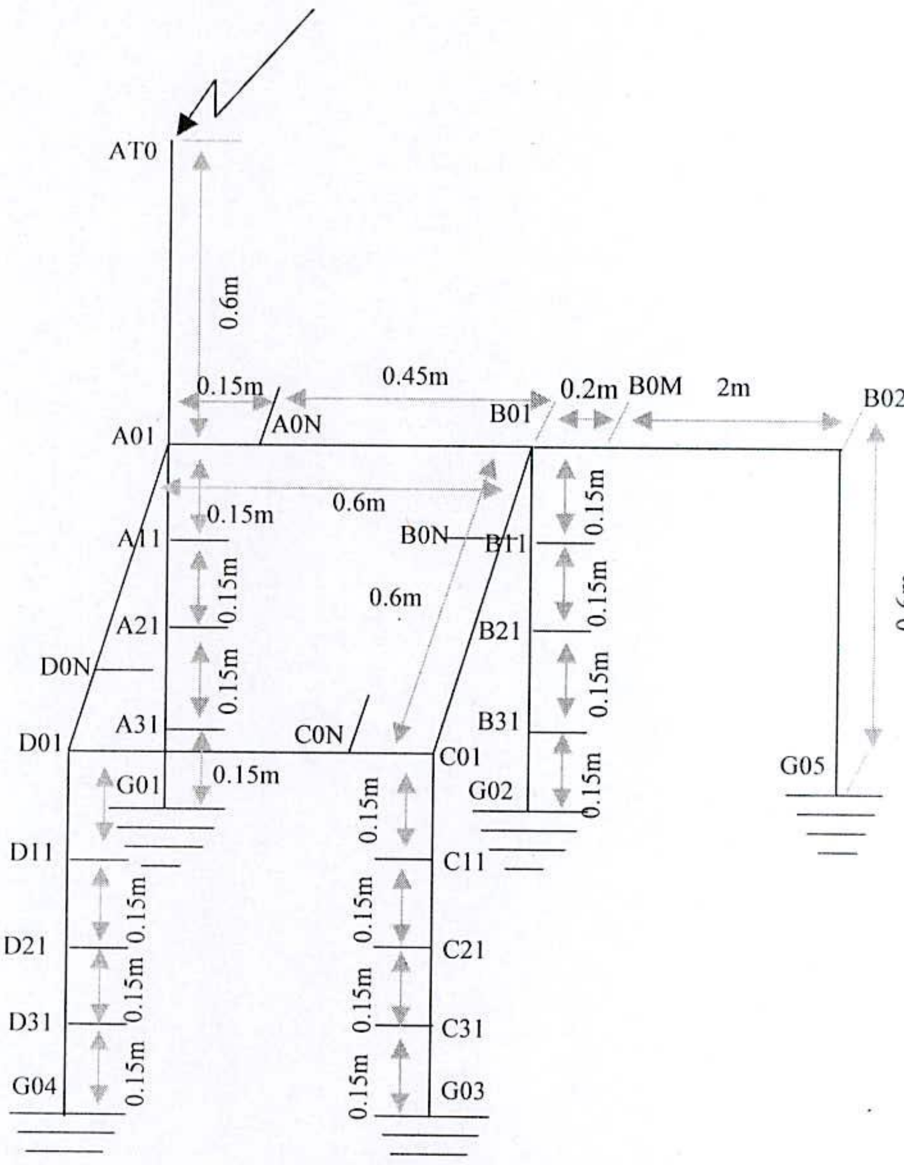


Fig. 43 Control Building-3 which have four segments of each conductor legs and two segments of overhead conductor.

6.4.1 Voltage Analysis of Control Building with Vertical Injection (Four Segments of each Conductor Legs and two segments of each Conductor Parallel to the Ground)

It is shown in Fig. 44 the voltage characteristics of the control building of vertically applied voltage and each conductor leg is divided into four segments and overhead conductor line divided into two segments of the control Building. 40 ns is taken for one complete pulse-width and 5V is applied for surge representation. There consists small delay time in the voltage waveform before the beginning of rising point. The delay time is 2.6 ns and the pulse of the voltage wave-shape is approximately 10 ns.

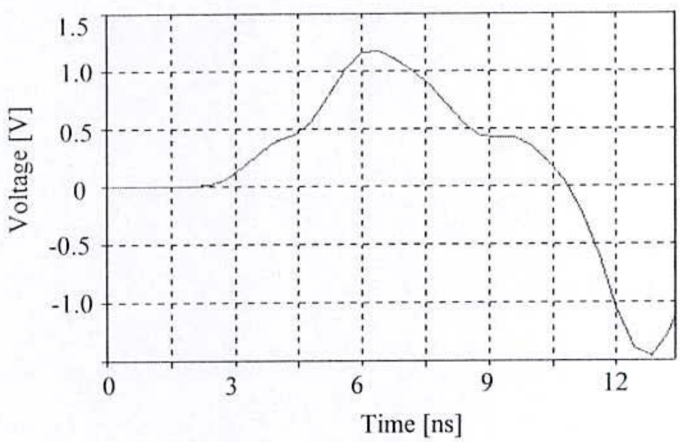


Fig. 44 Simulation voltage of control building-3.

So that from the above voltage waveform of measuring voltage curve of Fig. 44 is shown that voltage rises at 2.6 ns and start falling at 6.3 ns. That is 0.4 ns more delay than that of previous model. The rising time of this model shown in the Fig. 44 is 3.7 ns. Now if the surge current propagates along the tower at the speed of light, the reflected wave from the ground should return to the tower top after twice of the tower travel time which is 4 ns for the structure of the model of Fig. 43. So that for the structure of the model of Fig. 43 indicates that a negative voltage wave arrives at the tower top before the arrival of the reflected wave from the ground.

6.4.2 Current Analysis of Control Building with Vertical Injection (Four Segments of each Conductor Legs and two segments of each Conductor Parallel to the Ground)

From the simulated wave-shape of the Figs. 45a, 45b, 469a and 46b shows the characteristics of injected current, input current, segment current and ground current respectively. Also the current wave shape shows the rising time, delay time and reflection time. Here in the Fig. 38a shows the injected current, Fig. 45b shows four curves for the upper segment of each conductor leg. Fig. 46a and 46b shows middle segment and ground current respectively of each conductor leg. Each input current have some delay time and reflection time for some short length.

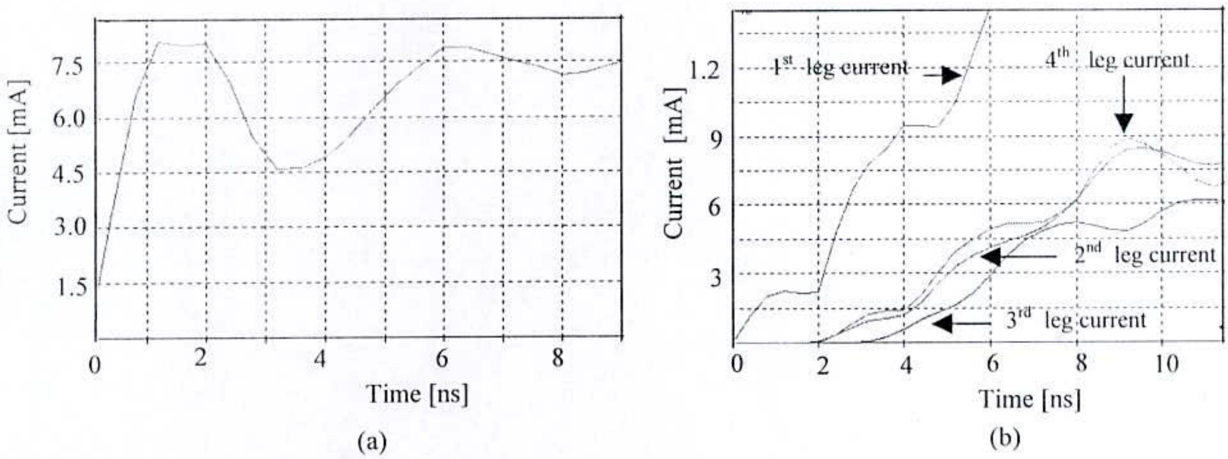


Fig. 45 (a) Injected current of the same model, (b) Upper segment current of each conductor Leg of the model.

The characteristics of the injected and segment current shown in the Fig. 45b, 1st curve starts from origin and no delay time, because node A01 is the first point and surge current didn't propagate any distance, on the other hand current of 2nd and 3rd curve starts with same delay time 2 ns as the calculated value, because they propagate same distance and current of 4th curve starts with more delay time 3.7 ns which is very small differences from the calculated value, the calculated value is 4 ns. It indicates that a negative voltage wave arrives at the tower top before the arrival of the reflected wave from the ground The reflection times of all the input current are same 2 ns.

In the Fig. 46a shows the upper segment current of the control building have some delay time for some short length 0.6 m and 1.2 m, the reflection time of each segment current is 6 ns. From the model of Fig. 43 shows current lead wire is 0.6 m and 1st and 2nd curve is the same distance of length 0.6 m from the node A01. So the delay time of the current of 1st and 2nd is same 2 ns. Again the node C01 is longer length than the node B01 and D01, so the delay time for this current is 3 ns which is almost equal to the calculated value. The rising time of each segment current is 3.2 ns.

Now Fig. 46b shows all the ground current of each conductor leg have also delay time , reflection time and rise time . The ground current of 2nd and 3rd curve have the same delay time 2.5 ns for surge current propagates same distance, 1st curve is for 1 ns and the current is for 3.5 ns.

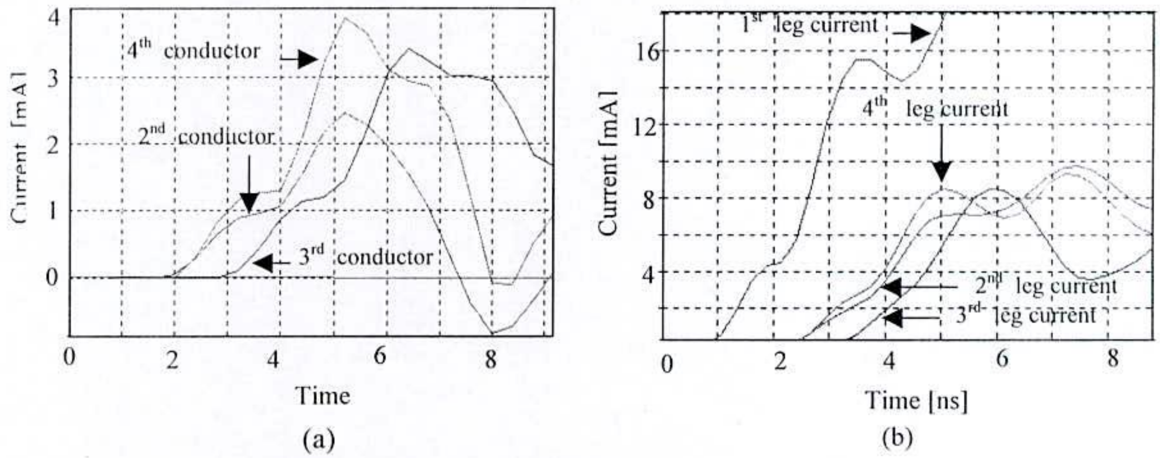


Fig. 46 (a) Segment current of the over head line, (b) Ground current of each conductor.

For the ground current of 3rd conductor , surge current propagates greater length compare to the node G02 and G04. And the simulation rise time of all the ground current is 2.4 ns which is almost the same of calculated value for surge current propagates 0.6 m length of travelling time of the model shown in Fig. 43. And It is almost the same characteristics, describes of the model in Fig. 39.

6.4.3 Measurement of Surge Impedance of Control Building with Vertical Injection (Four Segments of each Conductor Legs and two segments of each Conductor Parallel to the Ground)

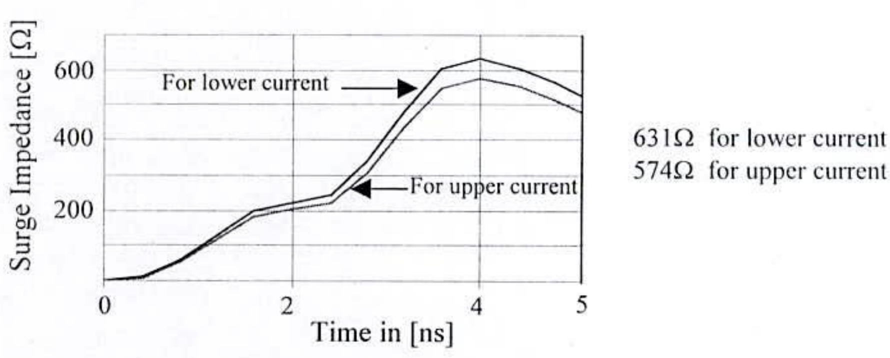


Fig 47 Surge Impedance of the control building –3.

Here in the Fig. 47 shows the Surge Impedance of Control Building with vertically applied voltage. There are two wave-shape shows in the Fig. 47 for surge impedance. The maximum surge impedance 631 Ω is for the minimum current of the input value of the model of the Fig. 43 and for the higher current, the surge impedance is 574 Ω. The lower value of surge impedance 574 Ω is for higher value of current where the reflection occurs, so this is the reliable surge impedance of this model of control Building.

6.5 Control Building With Horizontal Injection (No Segment of the Conductor Leg and overhead Conductor, Parallel to the Ground)

The model of the Fig. 48 shows a control building which have no segment of conductor leg and conductor, which is parallel to the ground. The Surge voltage is applied horizontally instead of vertically.

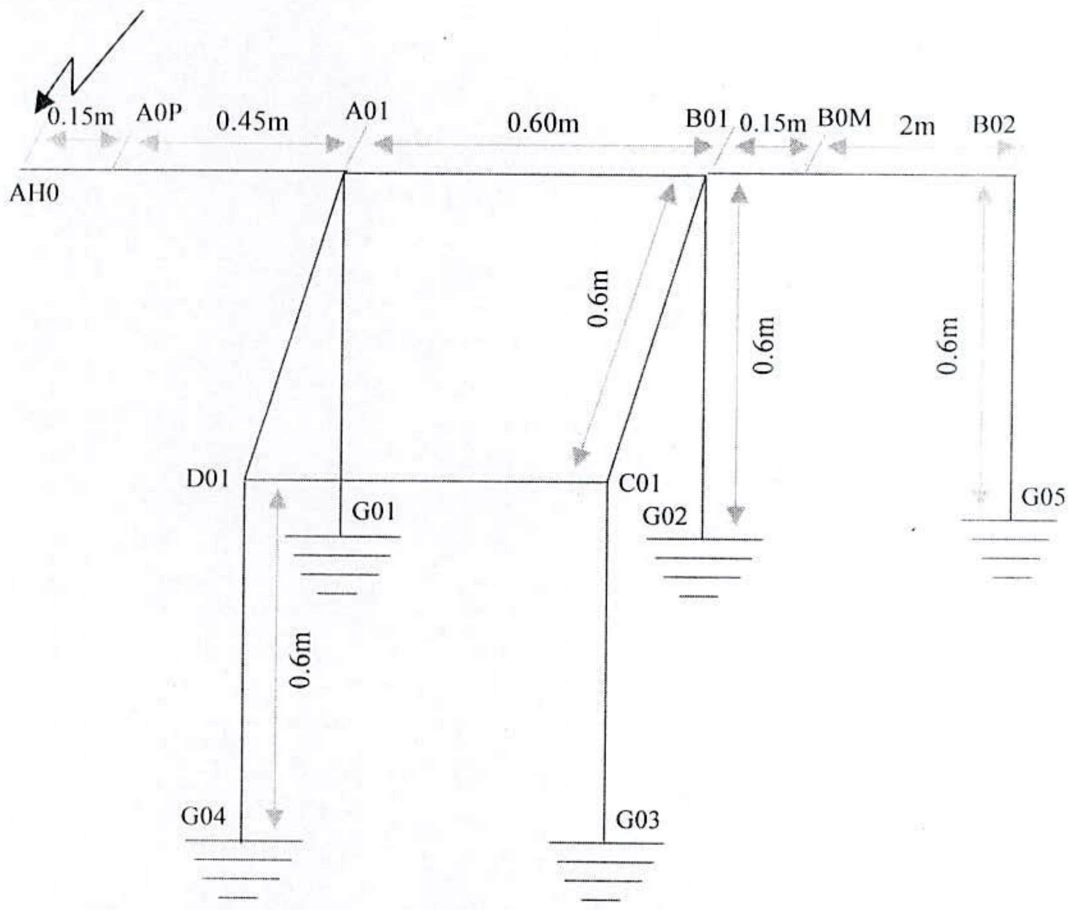


Fig. 48 Control Building-4 of Horizontally applied Voltage (No Segment of Conductor Leg and Overhead Conductor).

There are some differences among these models, that is conductors are divided into different segments in the previous model but here, no segment of conductor leg and overhead conductor. In this model the surge is applied at the edge of the current lead wire of control building horizontally instead of vertically. Now the characteristics of voltage, current and surge impedance is to be determined.

6.5.1 Voltage Analysis of Control Building with Horizontal Injection (No Segment of the Conductor Leg and overhead Conductor Parallel to the Ground)

The voltage characteristics of the control building shown in Fig. 49, that horizontally applied voltage with delay time, reflection time and rise time. 40 ns is taken for one complete pulse-width and 5V is applied for surge representation. There consists of small delay time in the voltage waveform before the beginning of rising point. The delay time is 2.5 ns and the pulse of the voltage wave-shape is approximately 6 ns.

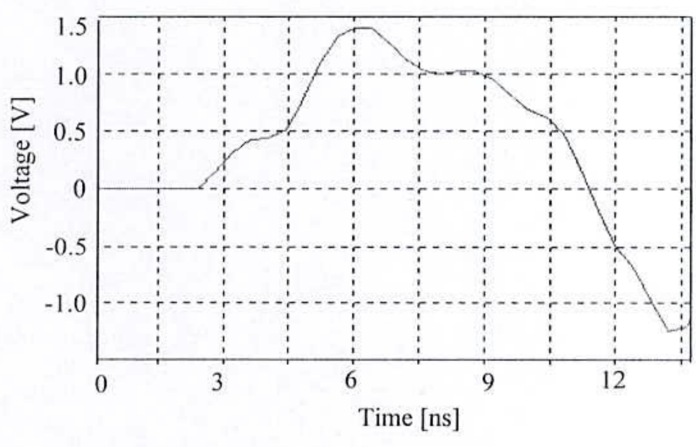


Fig. 49 Simulation voltage of the control building-4.

So that from the above voltage waveform of measuring voltage curve of Fig. 49 is shown that voltage rises at 2.6 ns and start falling at 6.5 ns. The rise time of this model shown in the Fig. 49 is 4 ns, which is equal to the calculated value 4 ns. The total time of one complete pulse width is 10.2 ns which is almost same of the previous model.

6.5.2 Current Analysis of Control Building with Horizontal Injection (No Segment of the Conductor Leg and overhead Conductor Parallel to the Ground)

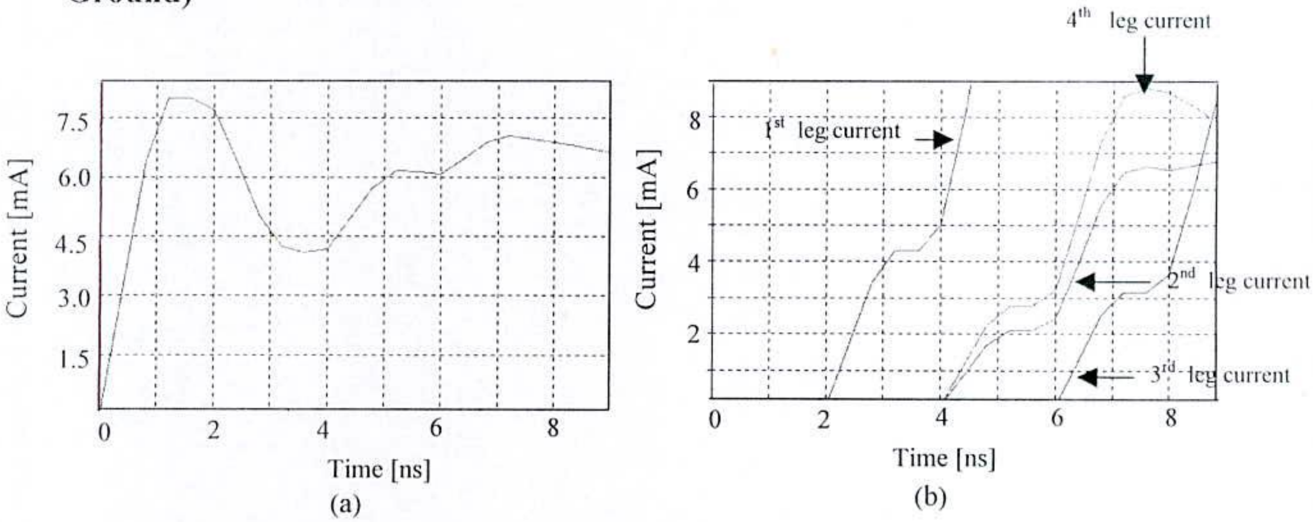


Fig. 50 (a) Injected Current of the tower, (b) Ground current of the conductor.

The current wave-shape of the above Fig. 50a and 50b shows the characteristics of injected current and ground current respectively. Also the current wave shape shows the rising time, delay time and reflection time. Here in the Fig. 50a shows the injected current and Fig. 50b shows all the ground the current of each conductor. Each current have some delay time and reflection time for some short length

The ground current of 2nd and 3rd curve have the same delay time 4 ns for surge current propagates same distance G02 and G04 in the Fig. 48, 1st curve, the current is for G01 and delay time is for 2 ns and 4th is for G04 the delay time is 6 ns which is almost equal to the calculated value. For the ground current of 4th curve, surge current propagates greater length compare to the node G02 and G04 in the Fig. 48. And the rise time of all the ground current is 4 ns which is almost the same of calculated value for surge current propagates 1.2 m length of travelling and return time of the model shown in Fig. 48

6.6 Control Building With Horizontal Injection (Two Segments of each Conductor Leg)

In the following Fig. 51 shows a model of control building which have two segments of each conductor leg. The Surge voltage is applied horizontally instead of vertically. The difference between previous and present model is, there was no segment of conductor leg in previous model but here in this model there are two segments of each conductor leg. In this model the surge is applied at the edge of the current lead wire of control building horizontally instead of vertically as like as previous model. Now the characteristics of voltage, current and surge impedance is to be determined

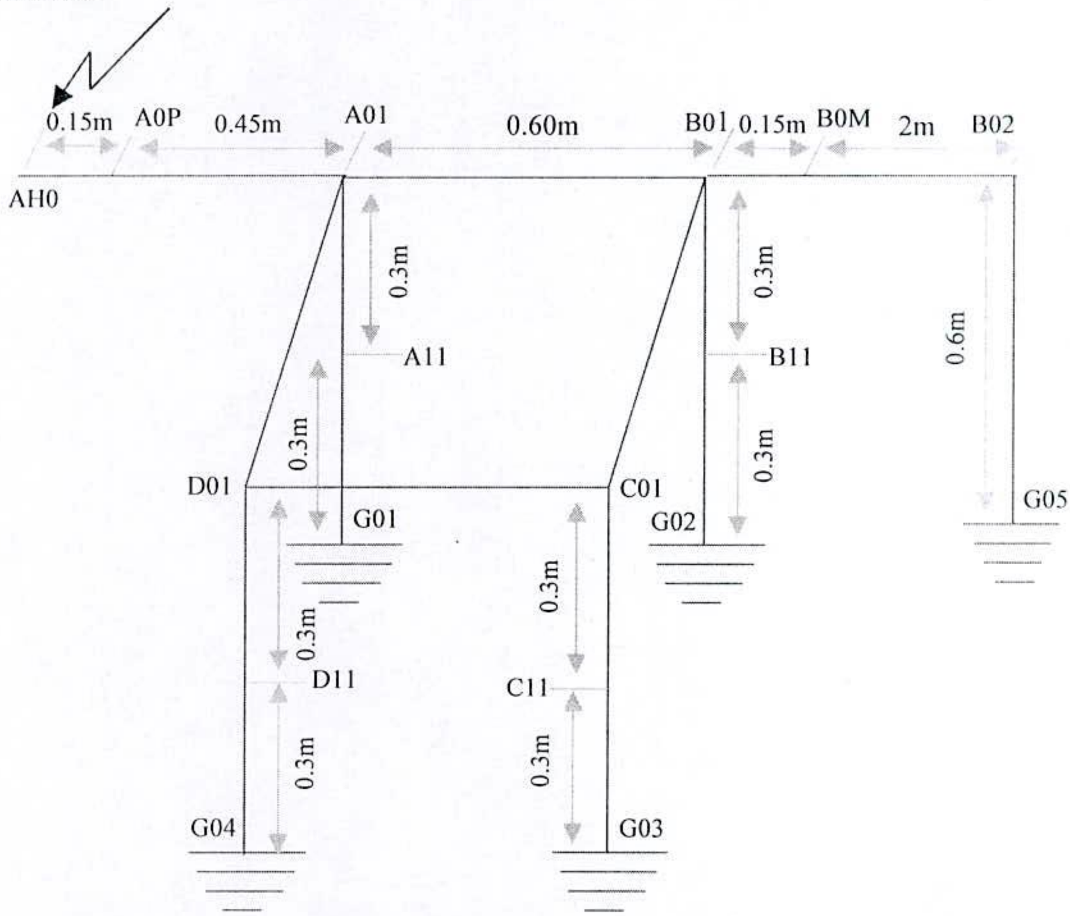


Fig. 51 Control Building-5 with horizontally applied voltage (Two segments of each conductor legs).

6.6.1 Voltage Analysis of Control Building with Horizontal Injection. (Two Segments of each Conductor Leg)

It is observed in the Fig. 52 that the characteristics of the voltage of the control building with horizontally applied voltage have delay time, reflection time and rise time. 40 ns is taken for one complete pulse-width and 5V is applied for surge representation. There consists of small delay time in the voltage waveform before the beginning of rising point. The delay time is 2.5 ns and the peak value of voltage is at 6.5 ns. So the rises time is 4 ns which is equal to the calculated value. So that from the following voltage waveform of Fig. 52 is shown that voltage rises at 2.5 ns and start falling at 6.5 ns.

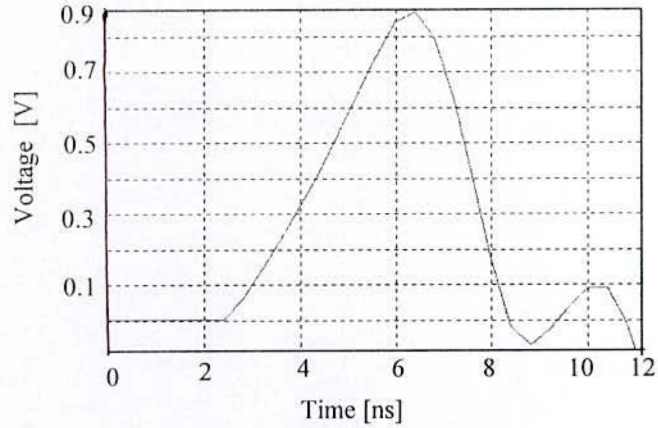


Fig. 52 Simulation Voltage of Control Building –5.

The rise time of this model shown in the Fig. 52 is 4 ns, which is equal to the calculated value 4 ns. Again the voltage starts increasing at 8.5 ns, that is the duration of reflection time is 6 ns.

6.6.2 Current Analysis of Control Building with Horizontal Injection. (Two Segments of each Conductor Leg)

It is observed in the Figs. 53a, 53b and 53c that the characteristics of injected current, input current and ground current respectively. Also the current wave shape shows the rising time, delay time and reflection time. Here in the Fig. 53a shows the injected current, Fig. 53b shows the input current or upper segment current of all the conductor and Fig. 53c shows the ground current of each conductor leg. Each input current have some delay time and reflection time for some short length.

In Fig. 53b shows upper segment current of 1st curve starts from origin and no delay time, because node A01 in the Fig. 51 is the first point and surge current didn't propagate any distance, on the other hand current 2nd and 3rd curve starts with same delay time 2 ns as the calculated value, because they propagate same distance and current of 4th curve starts with more delay time 4 ns which is almost the same for calculated value, the calculated value is 4 ns. The reflection times of all the input current are same 2 ns.

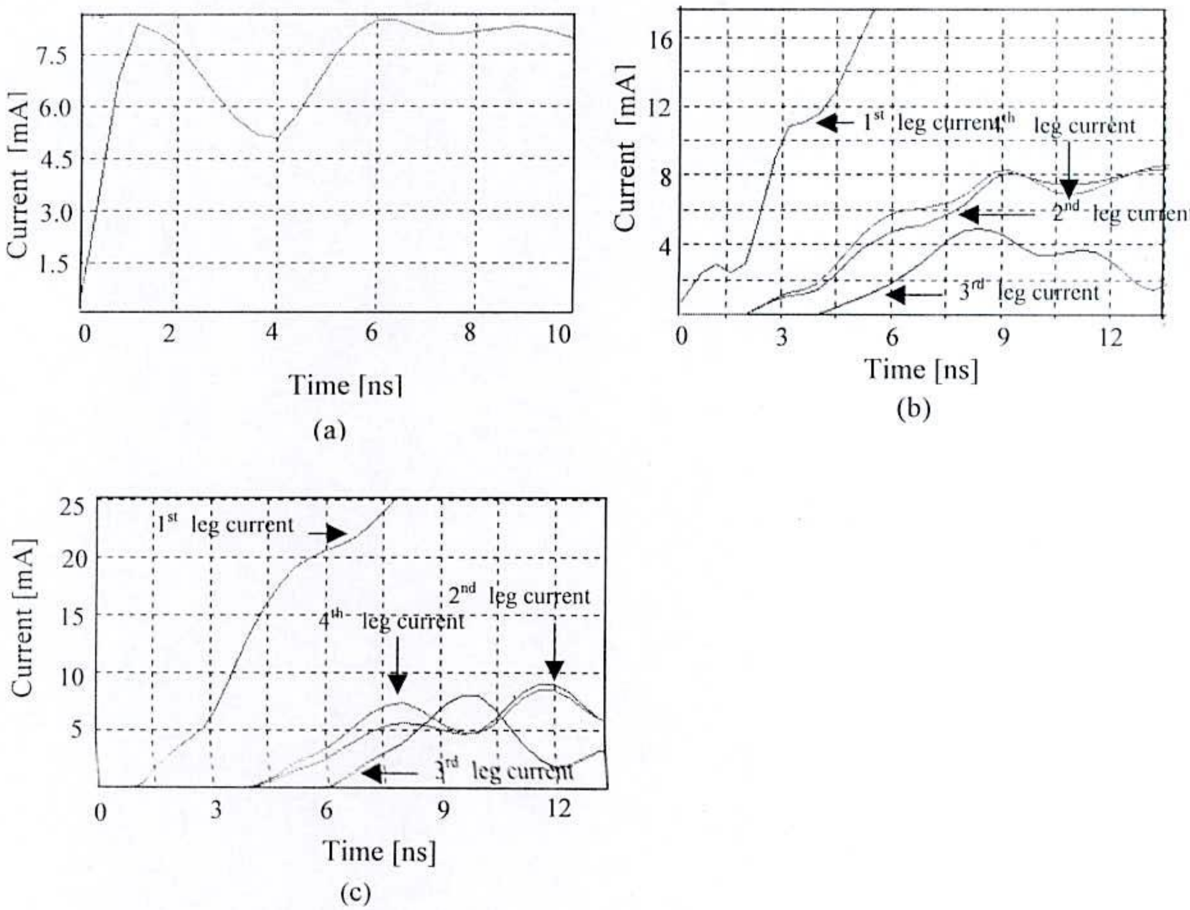


Fig. 53 (a) Injected current of the control building-5, (b) Upper segment current of each conductor leg, (c) Ground current of each conductor.

Now the Fig. 53c shows all the ground current of each conductor leg have also delay time , reflection time and rise time . The ground current of curve 2nd and 3rd curve have the same delay time, 4 ns for surge current propagates same distance, 1st curve is for 1 ns and 4th curve is for 5 ns which is almost equal to the calculated value. For the ground current of 4th curve , surge current propagates greater length compare to the node G02 and G04 shown in the Fig. 51. Again the figure shows the duration of rise time of 2nd , 3rd and 4th curve are 4 ns which is same for the calculated value for the model shown in the Fig. 51.

6.6.3 Surge Impedance Analysis of Control Building with Horizontal Injection. (Two Segments of each Conductor Leg)

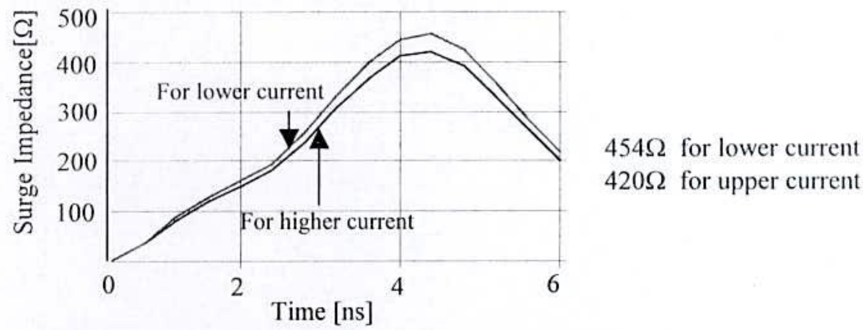


Fig. 54 Surge Impedance of the control building-5.

Here in the above Fig. 54 shows the surge impedance of control building with horizontally applied voltage. There are two wave-shapes shows in the Fig. 54 for surge impedance. The maximum surge impedance 454 Ω is for the lower value of input current of the model of the Fig. 51 and the lower value of surge impedance is for higher value of input current of the control building and the surge impedance is 420 Ω. And this is the reliable surge impedance for designing the control building.

6.7 Control Building With Horizontal Injection (Four Segments of each Conductor Leg)

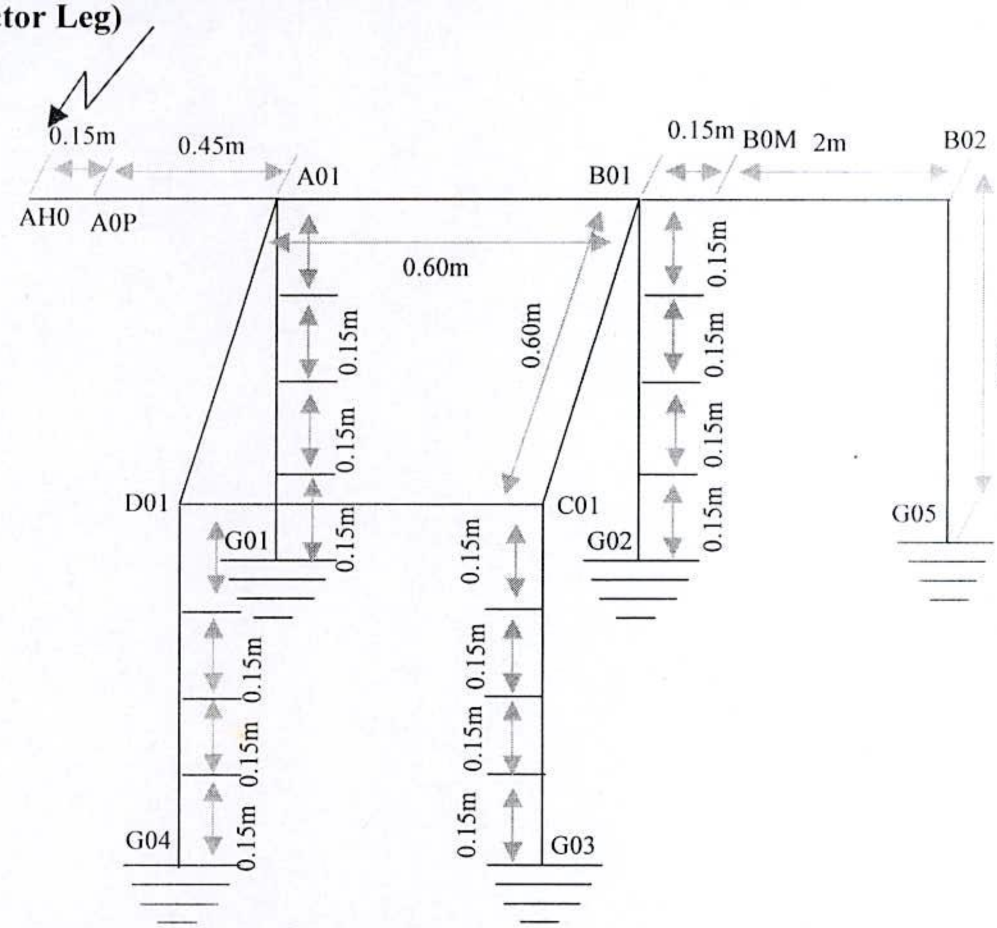


Fig. 55 Control Building-6 with Horizontal Injection (Four Segments of each conductor leg).

In the Fig. 55 shows a model of control building which have four segments of each conductor leg. The surge voltage is applied horizontally instead of vertically. The difference between previous and present model is, there ware two segments of each conductor leg in previous model but here in this model there are four segments of each conductor leg. In this model the surge is applied at the edge of the current lead wire of control building horizontally instead of vertically as like as previous model. Now the characteristics of voltage, current and surge impedance is to be determined

6.7.1 Voltage Analysis of Control Building with Horizontal Injection (Four Segments of each Conductor Leg)

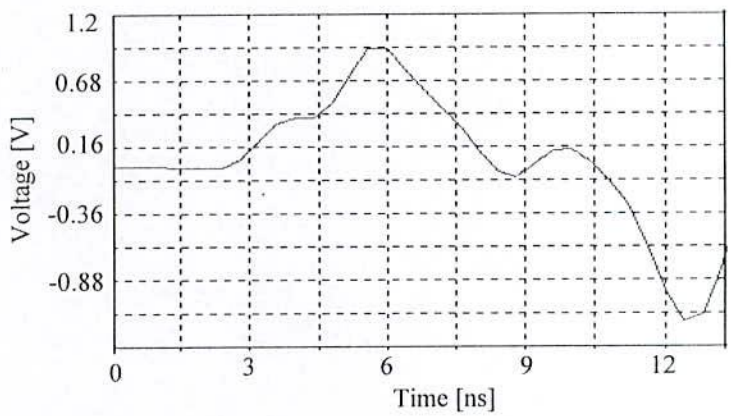


Fig. 56 Simulation Voltage of the control building-6.

By observing the Fig. 56 voltage-wave shows the characteristics of the control building of horizontally applied voltage and each conductor leg is divided into four segments. 40 ns is taken for one complete pulse-width and 5V is applied for surge representation. There consists small delay time in the voltage waveform before the beginning of rising point. The delay time is 2.5 ns and the pulse of the voltage wave-shape is approximately 10 ns.

So that from the above voltage waveform of measuring voltage curve of Fig. 56 is shows that voltage rises at 2.5 ns and start falling at 6 ns. The rising time of this model shown in the Fig. 56 is 3.5 ns. Now if the surge current propagates along the tower at the speed of light, the reflected wave from the ground should return to the tower top after twice of the tower travel time which is 4 ns for the structure of the model of Fig. 55. So that for the structure of the model of Fig. 55 indicates that a negative voltage wave arrives at the tower top before the arrival of the reflected wave from the ground.

6.7.2 Current Analysis of Control Building with Horizontal Injection (Four Segments of each Conductor Leg)

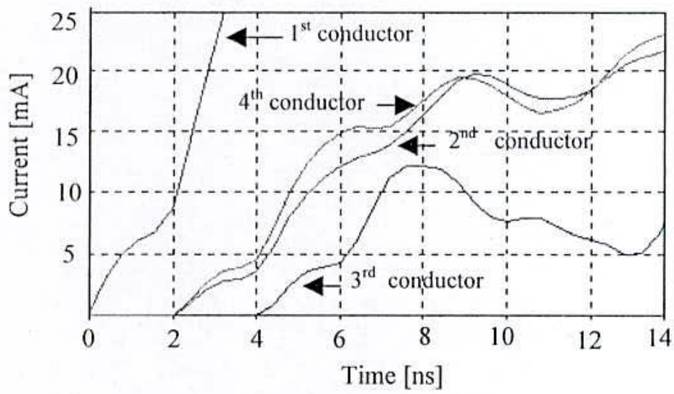


Fig. 57 Upper segment Current of the Control Building-6.

From the current wave-shape of the above Figs. 57, 58a and 58b shows the characteristics of input current or upper segment current , segment current and ground current respectively. Also the current wave shape shows the rising time, delay time and reflection time. Here in the Fig. 57 shows all the input current of different conductor legs and all the ground current of the conductors. Each input current have some delay time and reflection time for some short length. In Fig. 57 shows the 1st curve of the input current starts from origin and no delay time, because node A01 in the model is the first point and surge current didn't propagate any distance, on the other hand input current of 2nd and 3rd curve starts with same delay time 2 ns as the calculated value, because they propagate same distance and current 4th curve starts with more delay time 4 ns which is exact to the calculated value 4 ns. The reflection times of all the input current are same 2 ns.

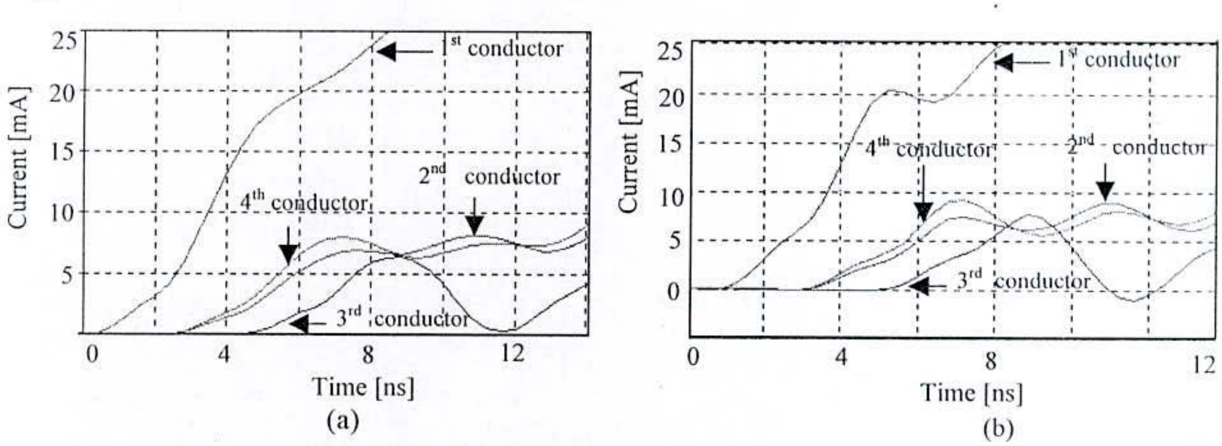


Fig. 58 (a) Middle segment current of control building, (b) Ground current.

It is observed in the Fig. 58a that the middle segment current of all the conductors have some delay time for some short length of 0.6 m and 1.2 m.

Now Fig. 58b shows all the ground current of the control building of each conductor leg have also delay time , reflection time and rise time . The ground current of 2nd and 3rd curve starts from same point and have same delay time 3.8 ns for surge current propagates same distance, 1st curve is for 1.8 ns and 4th is for 5.8 ns. For the ground current of 4th curve, surge current propagates greater length compare to the node G02 and G04 shown in the Fig. 55. And the rise time of all the ground current is 4 ns which is almost the same of calculated value for surge current propagates 1.2 m length of travelling and return time of the model shown in Fig. 55. And It is almost the same characteristics, describes of the model in Fig. 39

6.7.3 Measurement of Surge Impedance of Control Building with Horizontal Injection (Four Segments of each Conductor Leg)

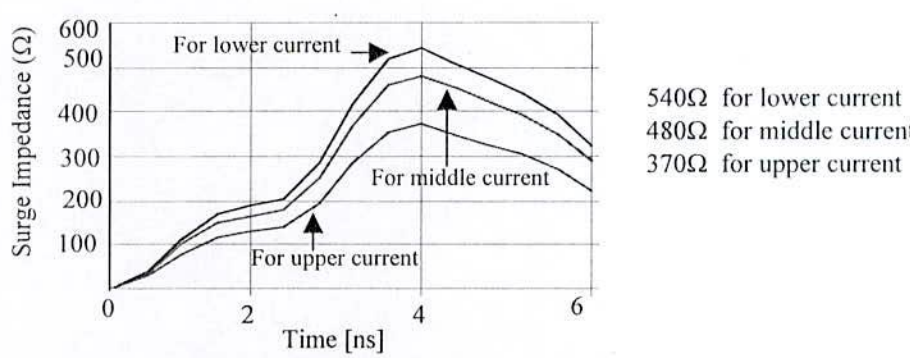


Fig. 59 Surge Impedance of the control building –6.

Here in the above Fig. 59 shows the surge impedance of control building with horizontally applied voltage. There are three wave-shape shows in the Fig. 59 for surge impedance. The maximum surge impedance 540 Ω is for the lower value of the input current of the model of the Fig. 55 and the middle surge impedance is for middle current, the surge impedance is 480 Ω and the lower impedance is for the upper value of current and surge impedance is 370Ω. The average value that is mid-level of surge impedance is suitable for designing the model of Fig. 55.

6.8 Control Building With Vertical Injection (Current Lead wire placed at the Center of the Diagonal Line of Control Building)

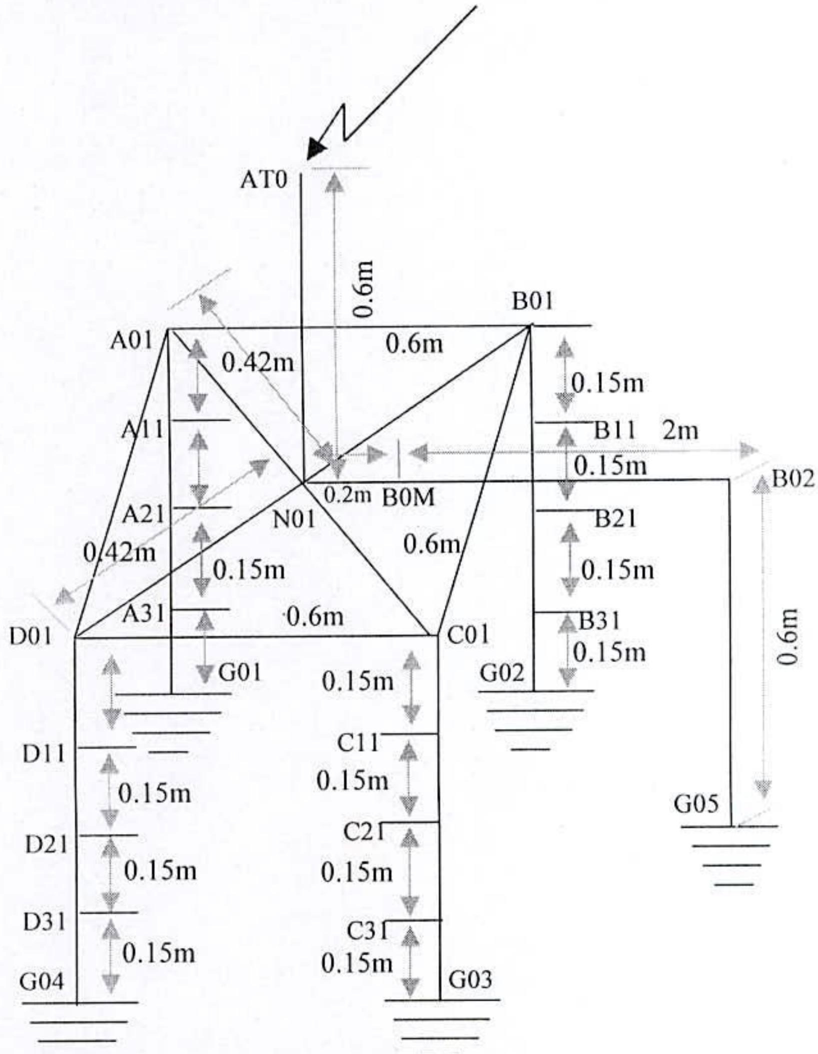


Fig. 60 Control Building-7 with Vertical Injection (Current lead wire placed at the diagonal of the control building).

In the above Fig. 60 shows a model of control building which have four segments of each conductor leg. The Surge voltage is applied horizontally instead of vertically. There are great differences between previous models and present model. Here voltage is applied vertically at the center of the diagonal line of control building and the conductor leg is divided into four segments. Now the characteristics of voltage, current and surge impedance is to be determined

6.8.1 Voltage Analysis of Control Building with Vertical Injection (Current Lead wire placed at the Center of the Diagonal Line of Control Building)

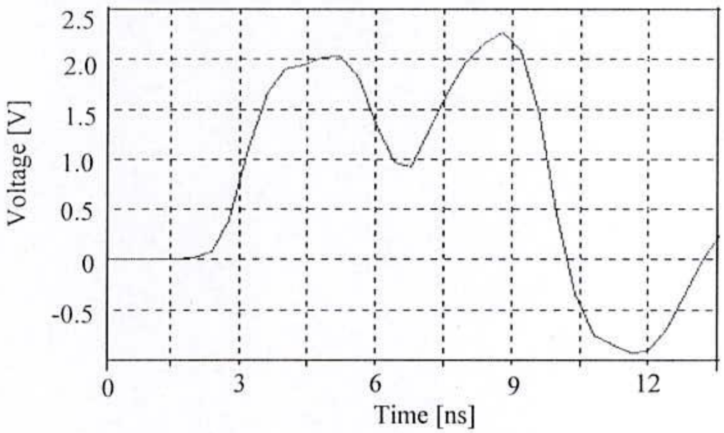


Fig. 61 Simulation Voltage of the control building.

The voltage characteristics of the control building with horizontally applied voltage shows in the Fig. 61 and each conductor leg of the control building is divided into four segments. One complete pulse-width is taken for 40 ns and 5V is applied for surge representation. There consists small delay time in the voltage wave form before the beginning of rising point. The delay time is 2 ns and the pulse of the voltage wave-shape is approximately 10 ns.

So that from the above voltage waveform of Fig. 61 is shown that voltage rises at 2 ns and start falling at 8.8 ns. The rising time of this model shown in the Fig. 61 is 6.8 ns which is exact to the calculated value.

6.8.2 Current Analysis of Control Building with Vertical Injection (Current Lead wire placed at the Center of the Diagonal Line of Control Building)

The current wave-shape is observed in the Figs. 62a, 62b and 62c that shows the characteristics of injected current, input current and ground current respectively. Also the current wave shape shows the rising time, delay time and reflection time. In the Fig. 62a shows the injected current, 62b shows the input current of the conductor leg, and 62c shows the all ground current of the control building. Each input current have also some delay time and reflection time for some short length.

In Fig. 62b shows all the upper segment current of the control building and starts 1st curve from origin and no delay time, because node A01 in the Fig. 60 is the first point and surge current didn't propagate any distance, on the other hand current 2nd and 3rd curve starts with same delay time 2 ns as the calculated value, because they propagate same distance and current 4th curve starts with more delay time 3 ns which is almost the same for calculated value.

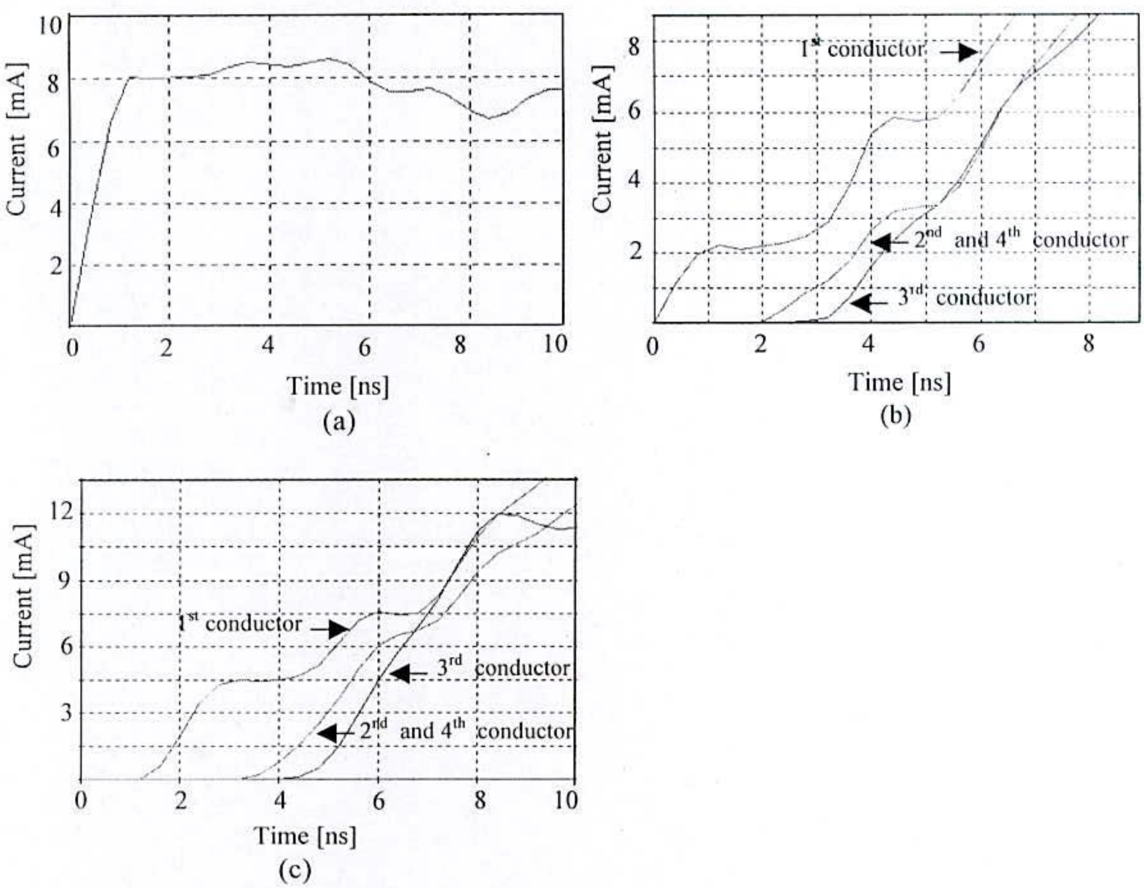


Fig. 62. (a) Injected current , (b) Upper segment current, (c) Ground current of all conductors.

Now Fig. 62c shows all the ground current of each conductor leg have also delay time , reflection time and rise time . The ground current 2nd and 3rd curve have the same delay time 3.5 ns for surge current propagates same distance, 1st curve is for 1.4 ns and the 3rd curve starts from 4.4 ns which is almost equal to the calculated value. For the ground current of 3rd curve, surge current propagates greater length compare to the node G02 and G04 shown in the Fig. 60 Again the figure shows the duration of rise time of all ground current are 4 ns which is same for the calculated value for the model shown in the Fig. 60.

6.8.3 Measurement of Surge Impedance of Control Building with Vertical Injection (Current Lead wire placed at the Center of the Diagonal Line of Control Building)

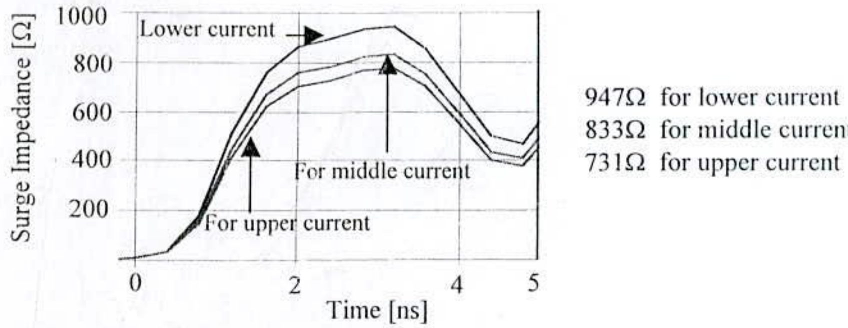


Fig. 63 Surge impedance of the control building-7.

Here in the above Fig. 63 it is shown that the Surge Impedance of Control Building with vertically applied voltage. There are three wave-shape shown in the Fig. 63 for surge impedance. The maximum surge impedance 947 Ω is for the lower value of the input current of the model of the Fig. 63 and the middle value of the surge impedance is for middle current of the input value, the surge impedance is 833 Ω and the lower impedance is for the upper value of current and surge impedance is 771 Ω. So the middle value of the surge impedance is reliable for design the control building.

6.9 Control Building with Vertical injection (Current Lead wire placed at the Center of the Control Building)

In the Fig. 64 it is shown that a model of control building which have four segments of each conductor leg. The Surge voltage is applied horizontally instead of vertically. There are great differences between previous model and present model. Here voltage is applied vertically at the center of the control building instead of diagonal line and the conductor leg is divided into four segments. Now the characteristics of voltage, current and surge impedance is to be determined

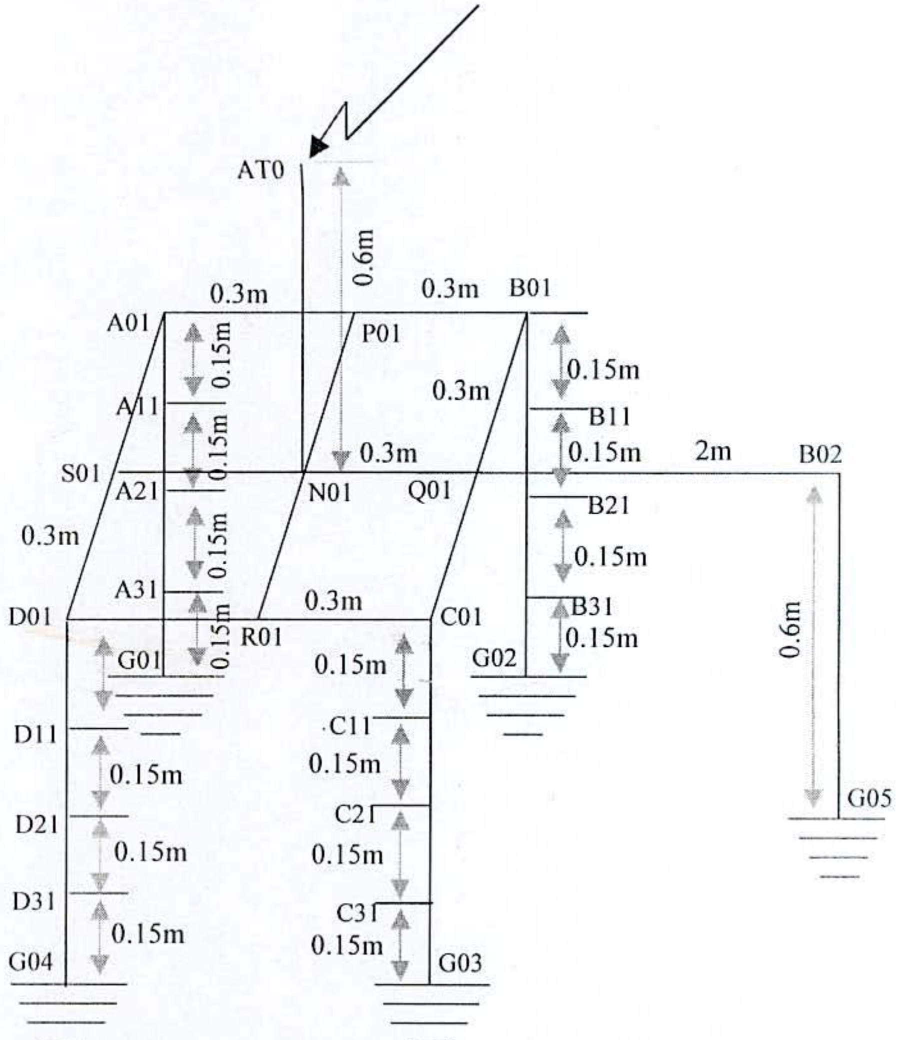


Fig. 64 Control Building-8 with Vertical Injection (Current Lead Wire placed at the Center of the Control Building).

6.9.1 Voltage Analysis of Control Building with Vertical Injection (Current Lead wire placed at the Center of the Control Building

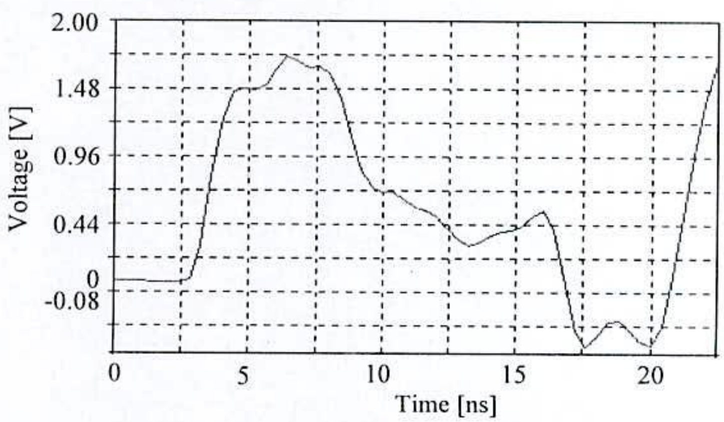


Fig. 65 Simulation Voltage of Control Building –8.

Fig. 65 voltage-wave shows the characteristics of the control building of vertically applied voltage and each conductor leg is divided into four segments. 40 ns is taken for one complete pulse-width and 5V is applied for surge representation. There consists small delay time in the voltage waveform before the beginning of rising point. The delay time is 2.6 ns and the pulse of the voltage wave-shape is approximately 15 ns.

So that from the above voltage waveform of Fig. 65 is shown that voltage rises at 2.6 ns and start falling at 6.5 ns. The rising time of this model shown in the Fig. 65 is 3.9 ns, which is almost to the calculated value.

6.9.2 Current Analysis of Control Building with Vertical Injection (Current Lead wire placed at the Center of the Control Building

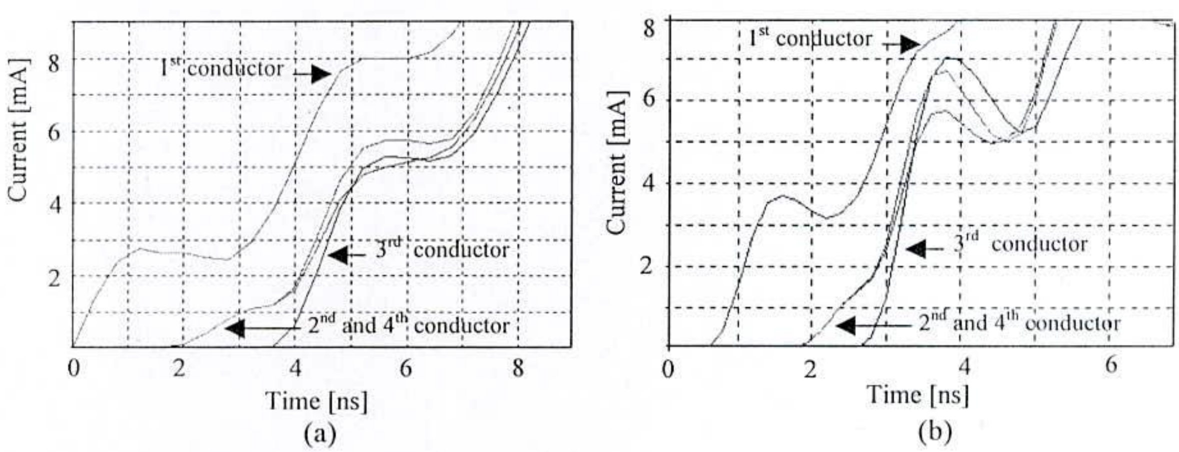


Fig. 66 (a) Upper segment current of the conductor leg, (b) Ground current of each conductor leg.

All the input currents or upper segment currents of the conductor legs are shown in the Fig. 66a that the current of 1st curve starts from origin and no delay time, because node A01 in Fig. 64 is the first point and surge current didn't propagate any distance, on the other hand current of 2nd and 3rd curve starts with same delay time 2 ns as the calculated value, because they propagate same distance and current of 4th curve starts with more delay time 3.8 ns which is almost the same for calculated value.

Now Fig. 66b shows all the ground current of each conductor leg have also delay time , reflection time and rise time . The ground current of the curve 2nd and 3rd have the same delay time 2 ns for surge current propagates same distance, 1st curve is for 0.7 ns and 4th curve of ground current is for 2.7 ns which is almost equal to the calculated value. For the ground current of curve 4, surge current propagates greater length compare to the node G02 and G04 in the Fig. 64. Again the figure shows the duration of rise time of the ground current are 4 ns which is same for the calculated value for the model shown in the Fig. 64.

6.9.3 Measurement of Surge Impedance of Control Building with Vertical Injection (Current Lead wire placed at the Center of the Control Building

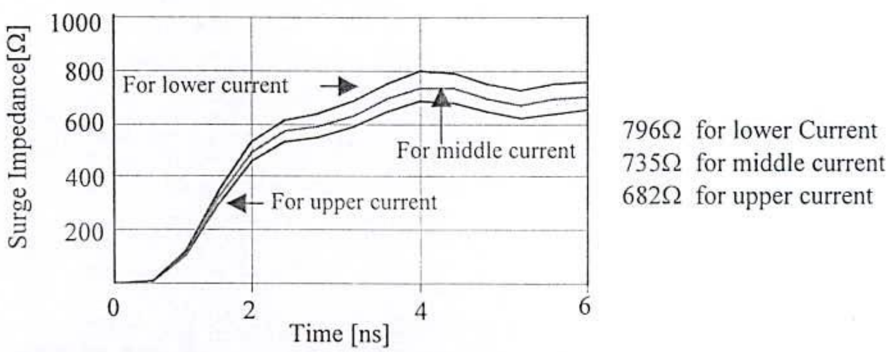


Fig. 67 Surge Impedance of the control building-8.

Here in the Fig. 67 it is shown the surge impedance of control building with vertically applied voltage. There are three wave-shape shows in the Fig. 67 for surge impedance. The maximum surge impedance 796 Ω is for the lower value of the input current of the model of the Fig. 64 and the middle value is for middle current, the surge impedance is 735 Ω and lower surge impedance is for upper current. And these values of surge impedance are reliable for designing this control building.

6.10 Control Building With Vertical Injection (Conductor placed at the Center of the Control Building)

In the following Fig. 68 shows a model of control building which have four segments of each conductor leg. The Surge voltage is applied horizontally instead of vertically. There are great differences between previous model and present model is conductor placed at the center of the control building instead of current lead wire and then current lead wire is placed at the top of the conductor. Then voltage is applied vertically at the center of the control building instead of diagonal line and the conductor leg is divided into four segments. Now the characteristics of voltage, current and surge impedance is to be determined

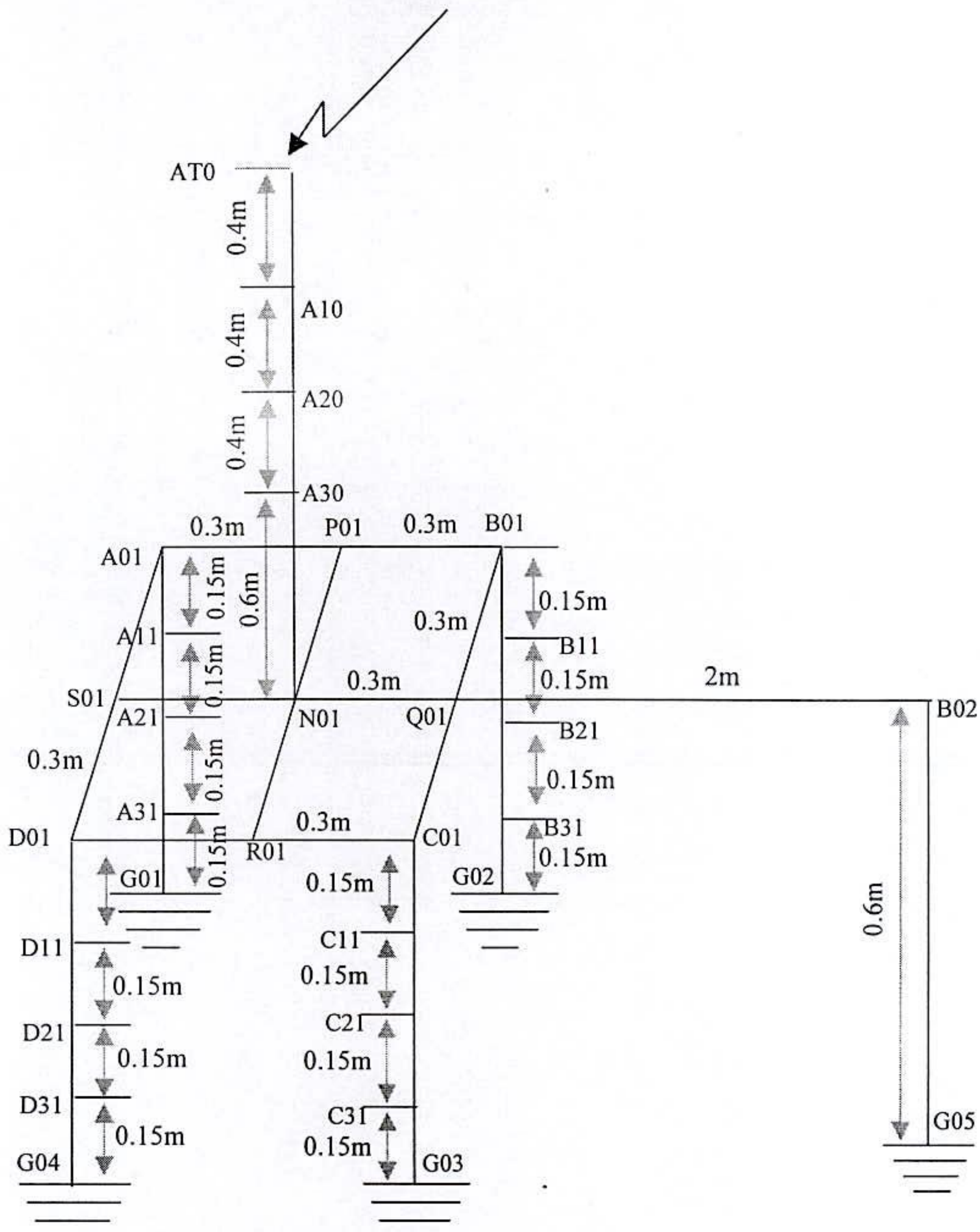


Fig. 68 Control Building-9 with Vertical Injection (conductor placed at the center of the Control Building).

6.10.1 Voltage Analysis of Control Building with Vertical Injection (Conductor placed at the center of the Control Building)

It is observed in the Fig. 69 that the voltage-wave shows the characteristics of the control building of horizontally applied voltage and each conductor leg is divided into four segments. 40 ns is taken for one complete pulse-width and 5V is applied for surge representation. There consists small delay time in the voltage waveform before the beginning of rising point. The delay time is 3.8 ns and the pulse of the voltage wave-shape is approximately 10 ns.

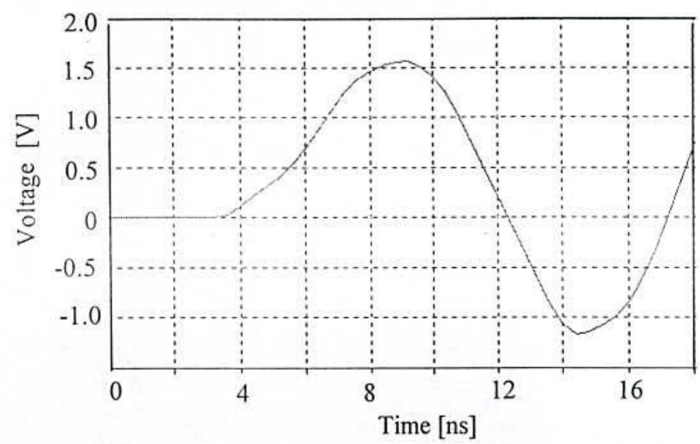


Fig. 69 Simulation Voltage of control Building –9.

So that from the above voltage waveform of Fig. 69 it is shown that voltage rises at 3.5 ns and start falling at 9.2 ns. The rising time of this model shown in the Fig. 69 is 5.7 ns, which is almost equal to the calculated value.

6.10.2 Current Analysis of Control Building with Vertical Injection (Conductor placed at the Center of the Control Building)

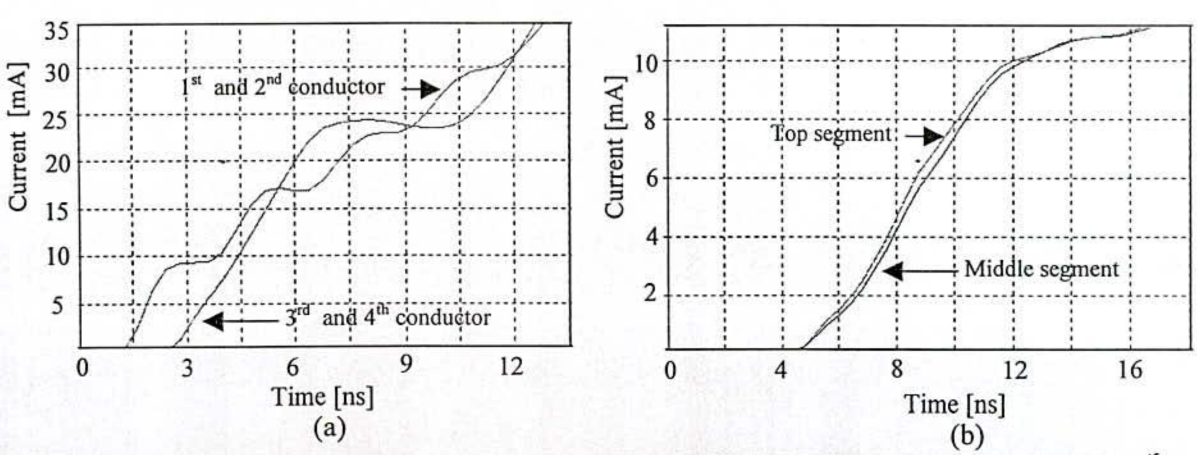


Fig. 70 (a) Segment current of the vertical conductor leg, (b) Upper segment current of the conductor

It is shown in Fig. 70a that the segment current A10-A20 and A30-N01 in the Fig. 68 have some delay time, rise time and reflection time. A10-A20 current starts with 1.7 ns delay and A30-N01 starts with 2.5 ns delay and its rises time is 4.5 ns. Now Fig. 708b shows the input current of the Fig. 68 A01-A11, B01-B11, C01-C11 and D01-D11 of the conductor leg of the control building have also delay time, reflection time and rise time . The input current or upper segment of the current starts with same delay time 5 ns for propagating the same distance of the control building and it rises at the peak value after 10 ns.

The figure shows these currents starts from same point that is the delay time is almost same for surge currents propagate the same distance. The reflection of all these currents is almost 10 ns.

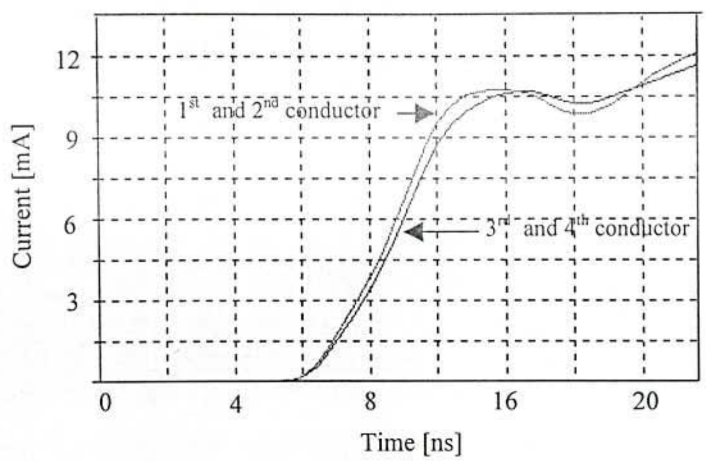


Fig. 71 Ground current of conductor legs.

Now Fig. 71 shows all the ground current G01, G02, G03 and G04 in Fig. 68 of each conductor leg have also delay time, reflection time and rise time. The ground current G01, G02, G02 and G04 have the same delay time 5.8 ns for surge current propagates same distance.

6.10.3 Measurement of Surge Impedance of Control Building with Vertical Injection (Conductor placed at the Center of the Control Building)

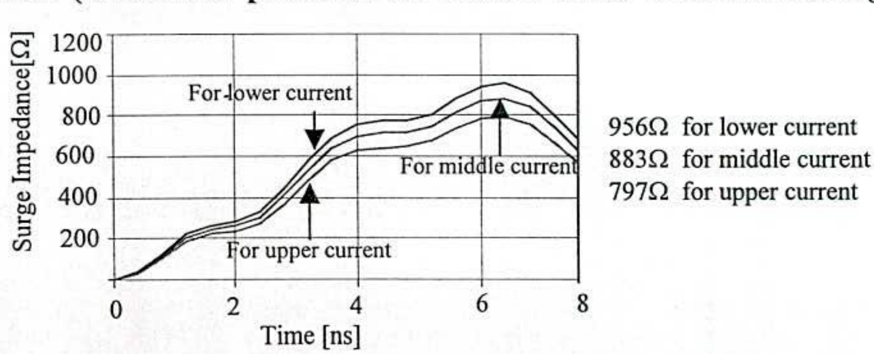


Fig. 72 Surge Impedance of the Control Building-9.

It is observed in the Fig. 72 that the Surge Impedance of control building with vertically applied voltage. There are three wave-shape shows in the Fig. 72 for surge impedance. The maximum surge impedance 956 Ω is for the lower value of the input current of the model of the Fig. 68 and the middle value of the surge impedance is for middle current the surge impedance is 883 Ω and the finally the lower value is for upper current and the surge impedance is 797 Ω. So the average value that is mid-level of surge impedance is suitable for designing the model like Fig. 68

6.11 Comparison of Surge Impedance of different model of Control Building (CB)

Here in the following table is given the comparative statement of surge impedance of different models of control building. From the table it is observed that those models whose current lead wire placed at the center of the control building those are the high surge impedance, that is control building 7, 8, 9 are high surge impedance for designing.

Table: 6 Comparison statement of surge impedance of different system of Control Building.

	CB-2	CB-3	CB-5	CB-6	CB-7	CB-8	CB-9
Upper	406Ω	631Ω	454Ω	540Ω	947Ω	796Ω	956Ω
Middle	-------	-------	-------	480Ω	833Ω	735Ω	883Ω
Lower	324Ω	574Ω	420Ω	370Ω	731Ω	682Ω	797Ω

CB-2 , CB-3 : Vertically applied Voltage
CB-7, CB-8, CB-9 : Vertically (Centrally) applied Voltage
CB-5, CB-6 : Horizontally applied Voltage

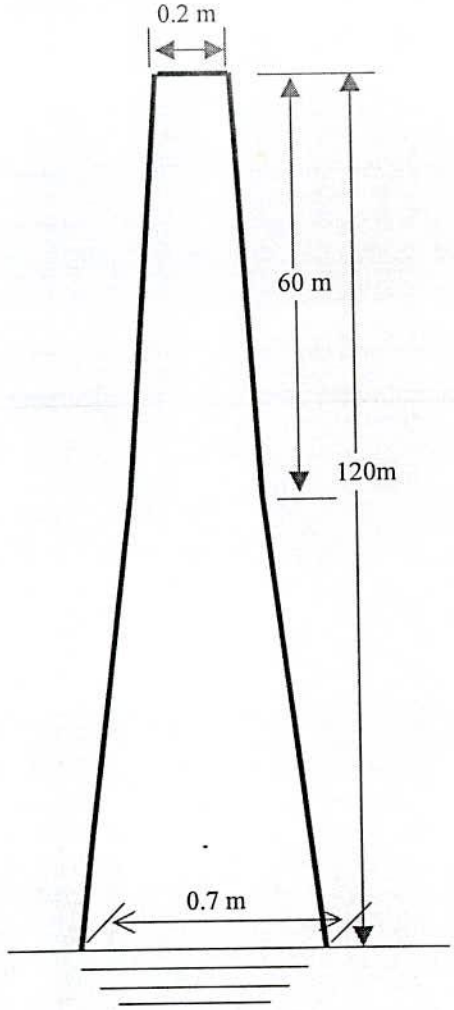
6.12 Summary

In this chapter surge impedance is calculated with different system of control building using EMTP. It is already shown in the 3rd chapter for single vertical conductor, surge impedance is greater for vertically applied voltage than horizontally applied voltage. Here in this chapter it is also observed that the surge impedance of control building is also the same effect as like the single vertical conductor. So for the measurement of surge impedance, it can easily compare from the from the comparison table that surge impedance of control building is greater for vertically applied voltage than horizontally applied voltage. Again Centrally applied voltage of control building is also investigated and the surge impedance is greater effect for this reason. Surge impedance is very high for centrally applied voltage than applied voltage at the edge or corner of the control building.

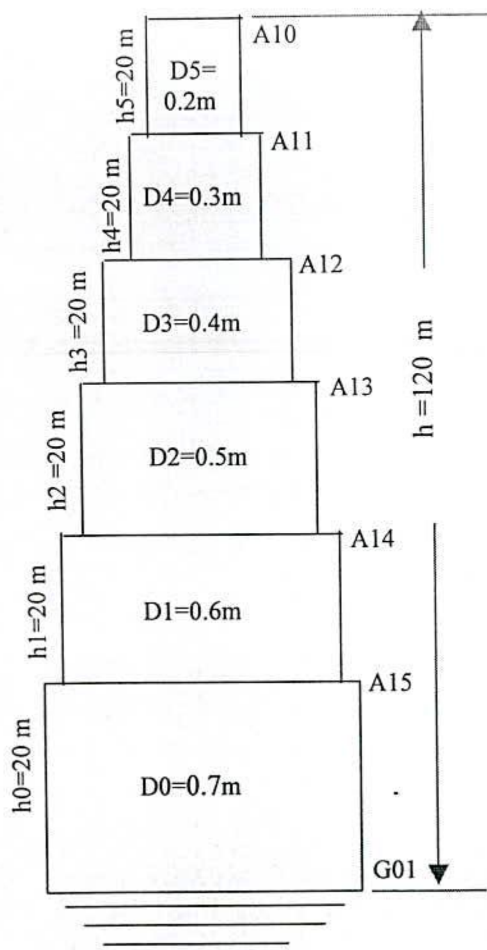
7. Surge Impedance Measurement for Actual Tower

7.1 Introduction

This chapter is very important for simulation work as it is used in practical purpose. In this chapter the surge impedance is simulated for actual tower which is for practical application. The tower model is shown in the Fig. 73, that the actual tower of four pole conductors or base-broadened tower. Here the tower is taken 120 m in length as actual tower and it is divided into six segments from bottom to the top of the tower for simulation, each of 20 m in length. Each segment of the tower is of different in diameter as in the Fig. 73b. In this work slant elements of the tower has not been considered for simplicity of simulation work.



(a) Main Pole



(b) Segment of the Pole

Fig. 73 Actual Tower

The voltage measuring wire of the arrangement of Fig. 74 is taken 150 m in length and the current lead wire is 240 m in length for actual tower and the voltage is applied vertically at the top of the base-broadened tower. In this section surge impedance is simulated only for vertical injection and then segment impedance has reduced for comparison with actual tower.

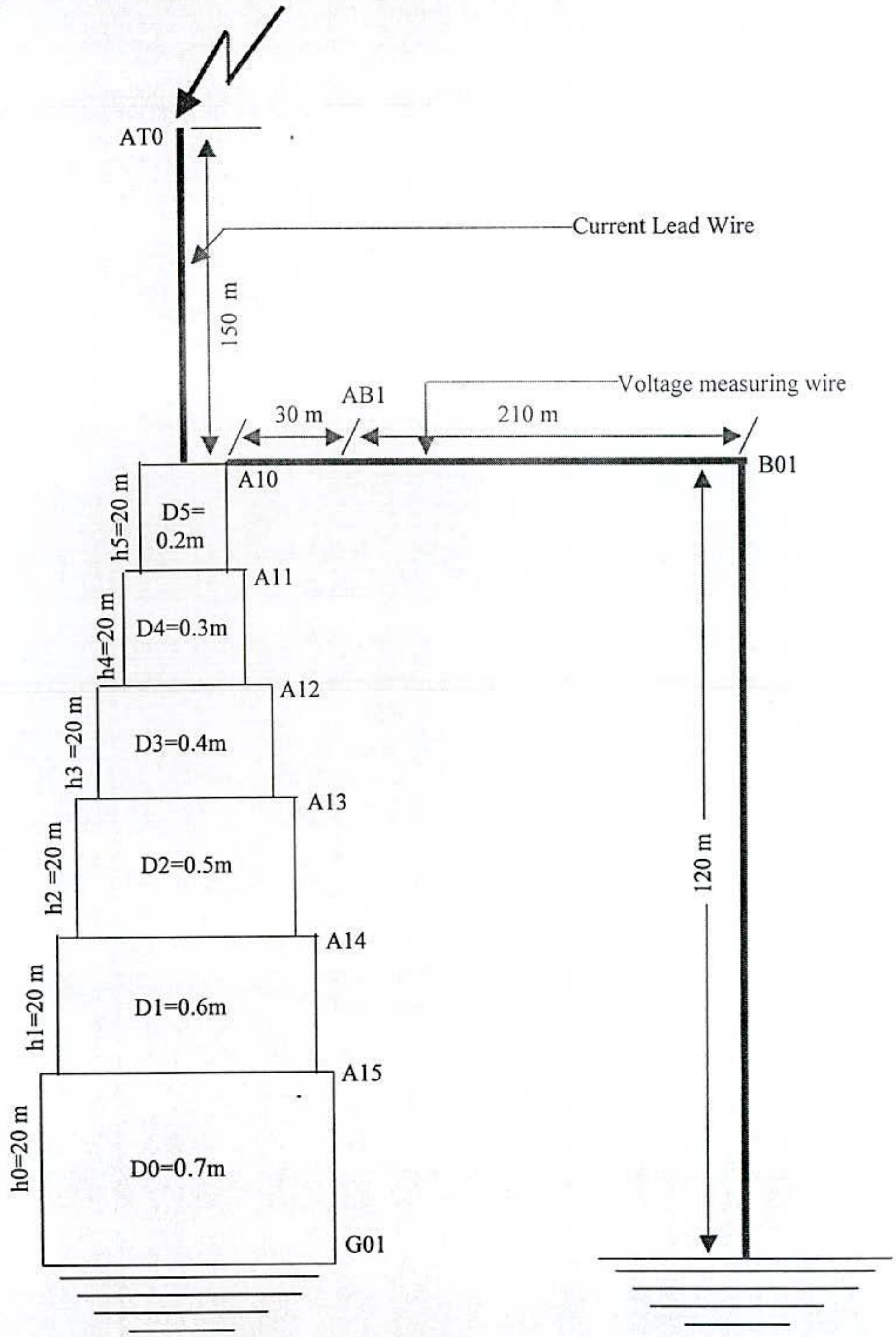


Fig. 74 Arrangement of the voltage measuring wire and current lead wire of the tower

7.1.1 Voltage Analysis of Actual Tower with Vertical Injection

Here the simulation is carried out only for vertical injection at the top of the current channel. In this section voltage is analyzed in the Fig. 75 by applying vertical injection at the top of the channel shown in the Fig. 74 .

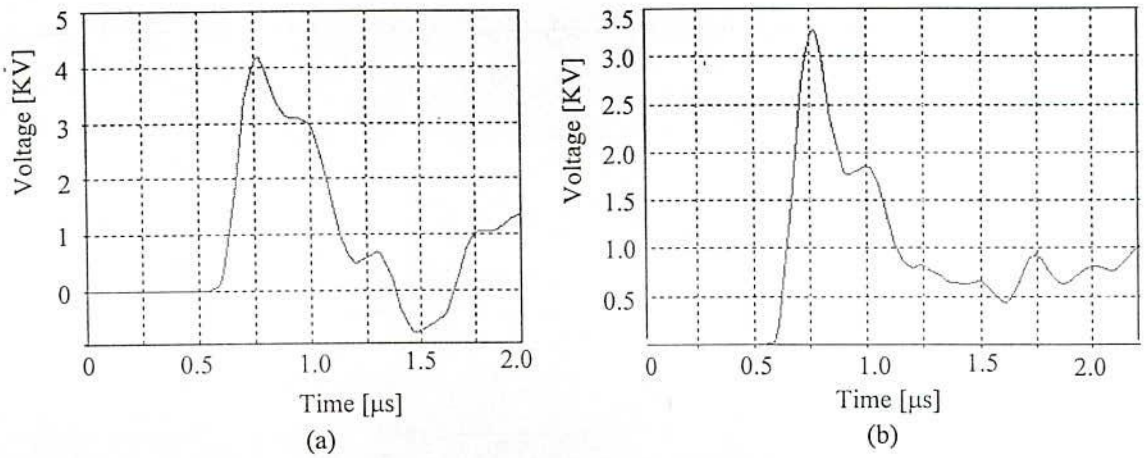


Fig. 75 (a) Simulation Voltage of the Tower, (b) Simulation voltage for reducing the impedance of current lead wire.

The characteristics of the voltage of actual tower is shown in the Fig. 75 . For simulation of actual tower 20 μs is taken for one complete pulse-width and 20 kV is applied voltage for surge representation. There exists some delay time in the voltage waveform before the beginning of rising point. The delay time is 0.6 μs for propagation of electromagnetic wave of 150 m length of current lead wire and the pulse of the voltage wave-shape is approximately 0.8 μs. Again in comparison of voltage between two wave in Fig. 75a and Fig. 75b it is seen that, peak voltage is 4.15 kV in Fig. 75a and negative voltage is induced at the tower foot before the occurrence of the reflection of the voltage wave propagating down from the tower top and 3.25 kV in Fig. 75b without any negative voltage. So the voltage wave form of Fig. 75b is reliable for reducing the impedance of current lead wire of the tower. And the voltage rises at the peak value of both the figure after 0.8 μs which is exact to the calculated value.

7.1.2 Current Analysis of Actual Tower with Vertical Injection

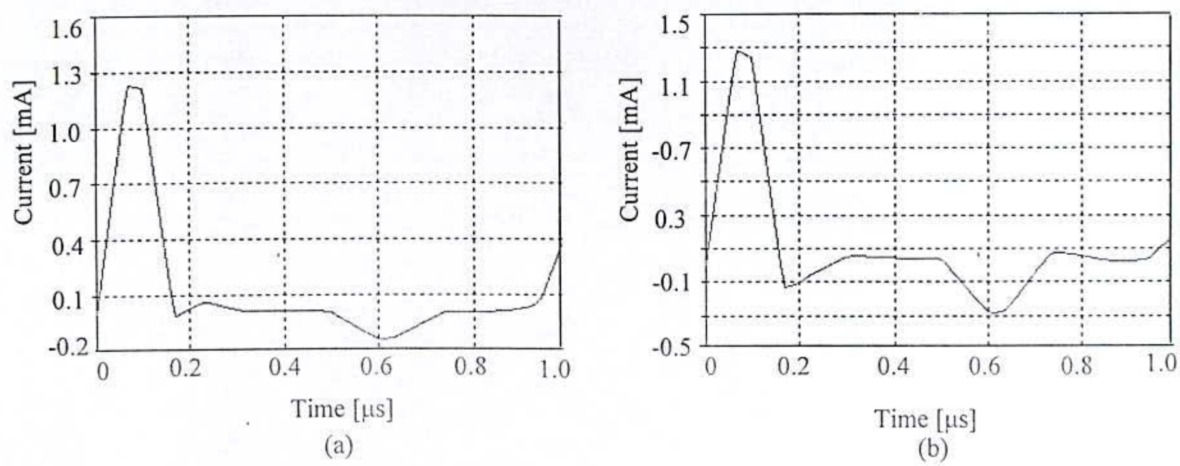


Fig. 76 (a) Injected Current of the tower, (b) Injected current of the tower (For reducing the impedance of current lead wire) .

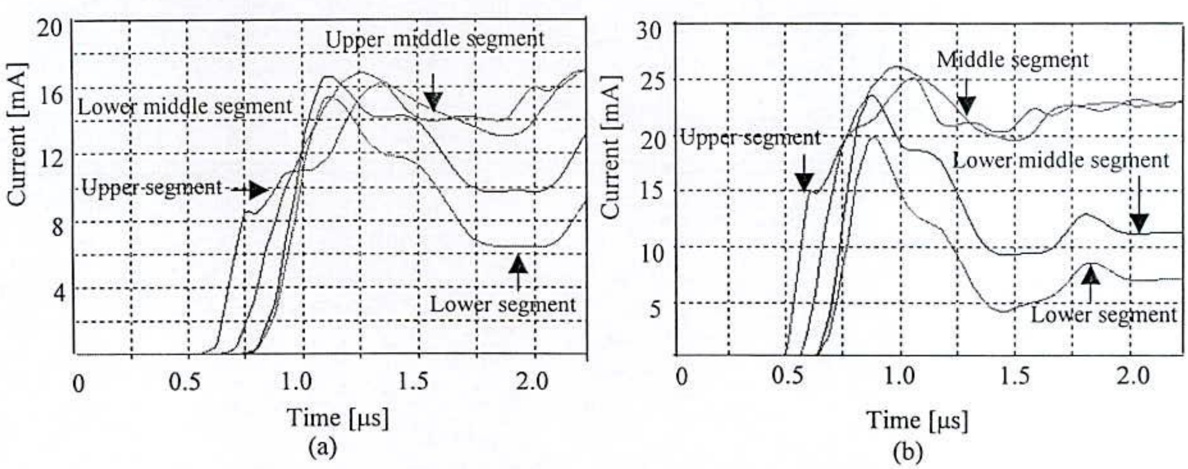


Fig. 77 (a) Different segments current of the tower, (b) Different segments current of the tower (for reducing the impedance of current lead wire)

For investigate the current wave shape it is observed in the Fig. 76 and Fig 77 that injected current is shown in the Fig. 76 and different segments current are shown in the Fig. 77. The current wave shape shows the rising time, delay time and the reflection time. It is shown in the Fig. 77a and Fig. 77b four segments current of actual tower. Fig. 77a and Fig. 77b all are the same currents but only the differences is Fig. 77b has reduced impedance of current lead wire of actual tower. Each segment current have some delay time for each segment length of 20 m and the duration of reflection time of each segment current is 12.75 μs. In the Fig. 77 shows the segment current, 1st curve is for the upper segment, 2nd is for the middle segment current and 3rd and 4th curve is for the lower segment current, each of the current have some delay time for some length, rise time and reflection time as discussed before in the chapter 3.

7.1.3 Surge Impedance Analysis of Actual Tower with Vertical Injection

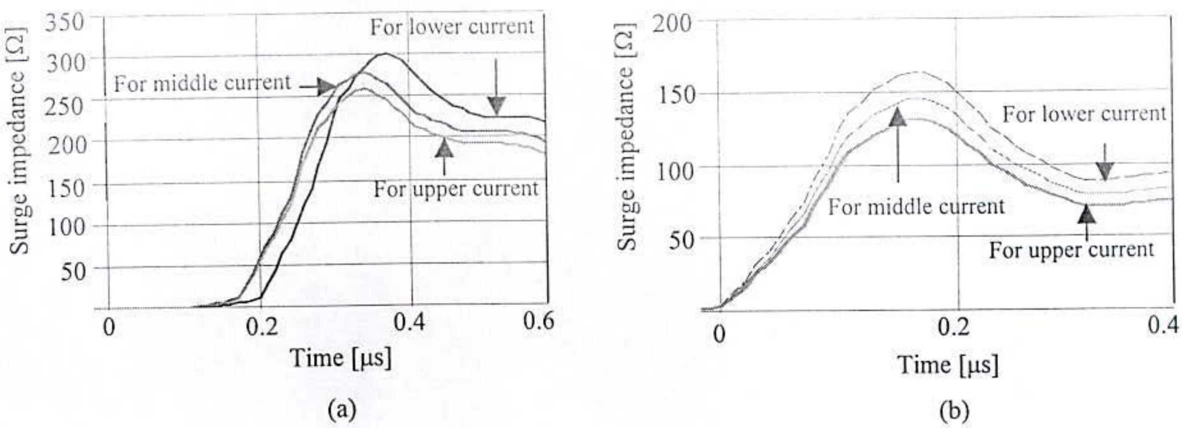


Fig. 78 Surge impedance characteristics (a) Surge impedance with vertical injection, (b) Surge impedance with vertical injection (for reducing the impedance of current lead wire).

Table : 7 Surge impedance comparison

Surge Impedance	Current Lead wire (150 m)	Current Lead wire (150 m) (Reduced Segment Impedance)
Upper Current	258 Ω	130 Ω
Middle Current	279 Ω	145 Ω
Lower Current	300 Ω	163 v
Theoretical	395 Ω	

Here in the above Fig. 78a and 78b shows the surge impedance curve of actual for vertically applied voltage. By investigating the Fig.78, it is shown that three curves is for surge impedance of upper, middle and lower current of 1st segment or input current of the actual tower. From the table: 7 it is shown that the maximum surge impedance in the Fig. 78a is 300 Ω for lower of the input current of the tower , the middle surge impedance is for middle current and the surge impedance is 279 Ω and the lowest surge impedance is 258 Ω is for upper current. Again it is shown in the Fig. 78b for surge impedance , the maximum surge impedance is 163 Ω for lower current and 145 Ω is for middle current and the lowest surge impedance is 130 Ω is for upper current. And these surge impedance are reliable of designing the actual tower. All these three surge impedance are close to the theoretical value.

7.1.4 Summary

In this chapter surge impedance is simulated using EMTP for actual tower. Normally actual tower is of different diameter so the surge impedance is also varies for different diameter. The theoretical values of surge impedances calculated from the theoretical formulas [25][26] are verified by comparing the computed on simple structures. The difference of surge impedance between theoretical value and simulation value is 24% at time $t = 2h/c$ for vertically applied voltage. Results measured on actual tower, therefore, it is employed in the practical calculation of the lightning phenomenon and electromagnetic behavior of a three dimensional system struck by lightning. Also, the traveling wave propagating at nearly the velocity of light is observed here. Again surge characteristics have some influence for the different diameter of the tower, from the simulation result it is shown that diameter is inversely proportional to the surge impedance which is already discussed in chapter 5.

8. Conclusions

From this work it is seen that electromagnetic transient behaviour of lightning surge on the vertical conductor are analysed using EMTP and compared one model using Numerical Electromagnetic Code (NEC-2). Voltage, Current and Surge response are analysed in the different models of the vertical conductor. Firstly, single vertical conductor of reduced scale model is investigated using different procedures, i.e. using the voltage applied on the top of the tower of vertically applied voltage, lower segment of the tower, horizontally applied voltage, influence of the frequency of line constant program and grounded the current lead wire is also taken into account. Base-broadened tower or four parallel conductors and other small vertical tower are also investigated. Voltage and Current response are simulated using EMTP and also compared with the calculated value.

Horizontally applied voltage are little influenced for the tower surge response Surge impedance for vertically applied is greater than that of horizontally applied voltage for single conductor and smaller for base-broadened four pole tower. For investigation the different frequencies of the line constant program, it is seen that frequency of line constant program is inversely proportional to the surge impedance. Another model for small height vertical tower is the greater effect of surge response using NEC-2. By using EMTP surge response is smaller than using NEC-2.

Secondly, the base-broadened four parallel tower response, there are different diameter of different segments of four parallel conductor, so the surge response is also different for different diameter. Surge response is inversely proportional to the diameter, i.e. if the diameter of the conductor increases, surge response will be decreased and if the diameter decreases surge response will be increased and it is also verified in this work.

Again surge impedance is analyzed for control building using EMTP. For this surge impedance is simulated in the control building using different system of applying lightning surge. There it is also shown that surge impedance is greater for vertically applied voltage than horizontally applied voltage. By using EMTP simulation it is seen that centrally applied voltage in the control building is very greater effect than applying at the edge of the control building. For simulation arrangement of the current lead wire and voltage measuring wire should be appropriate in length. For accuracy of the result, measuring wire will be perfect if propagation of the travelling time in the wire is larger than rising time, otherwise there negative voltage will arrive at the tower top before the arrival of the reflected wave from the ground. Finally surge impedance is investigated for the actual tower. The simulation results varies 24% from the calculated value.

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Appendix

Sample Input Data to EMTP

A) Input Data for Single Vertical Conductor(Without Ground) for EMTP in Ch.3

```
BEGIN NEW DATA CASE
C   Single Vertical Conductor with vertically applied source far from-
c   the the top
C RES(27-32);A(33-38);B(39-44);L(45-50);LINE(51,52);IPUNCH(53,54);IOUT
C (80)
C  AMPLITUDE(11-20);To(31-40);A1(41-50);T1(51-60);Tstop(71-80)
C567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234
C        1        2        3        4        5         6         7        8
 4.0E-10  4.0E-8
       1       1        1       1       1       1        0        2      0      0
-1A01   AB1                 0.036 5.12E22.99E8  0.30 1 0                          0
-1AB1   B01                 0.482 5.12E22.99E8  4.00 1 0                          0
-1A10   A11                 0.363 5.96E22.99E8  0.30 1 0                          0
-1A11   A01                 0.036 5.73E22.99E8  3.00 1 0                          0
-1A01   AG1                 0.048 5.06E22.99E8  0.40 1 0                          0
-1AG1   AG2                 0.072 4.86E22.99E8  0.60 1 0                          0
-1AG2   AG3                 0.036 4.60E22.99E8  0.30 1 0                          0
-1AG3   G01                 0.084 4.08E22.99E8  0.70 1 0                          0
-1B01   G02                 0.241 4.71E22.99E8  2.00 1 0                          0
 0G01                       50.0                                                  1
 0G02          G01                                                                1
 0A01   AG1                 0.1                                                   1
 0AG2   AG3                 0.1                                                   1
 0A10   A11                 5.1E2   0.0    0.0                                    1
 0AB1   B01                 5.0E4                                                 2
BLANK
BLANK
13A10         5.0E+0                4.0E-9     5.0E+0    40.0E-9    40.0E-9
BLANK
BLANK
BLANK
```

Input Data for Single Vertical Conductor(Without Ground) for Line Constant Calculation in EMTP in Ch.3

```
BEGIN NEW DATA CASE
C  SKIN(4-8); RESIS(9-16);IXTYPE(17,18);REACT(19-26);DIA(27-
34);HORIZ(35-42)
C · VTOWER(43-50);VMID(51-58)
C FREQ. CARD:EARTH RES(1-8); FREQ(8-18);FCAR(19-28);ICPR(30-
35);IZPR(37-42)
C ICAP(44);MODAL(69,70)
LINE CONSTANTS
$ERASE
METRIC
  1  0.5   21.50 4            0.10 0.10   0.10    0.10
BLANK
  1.7E-8  1.953E6          1 000010 010000 0                        1
BLANK
BLANK
$PUNCH
BEGIN NEW DATA CASE
BLANK
```

Input Data for Single Vertical Conductor (With Ground) for EMTP in Ch.3

```
BEGIN NEW DATA CASE
C   Single  Vertical Conductor  with  Horizontally  applied source far
c   from the the top
C RES(27-32);A(33-38);B(39-44);L(45-50);LINE(51,52);IPUNCH(53,54);IOUT
C (80)
C  AMPLITUDE(11-20);To(31-40);A1(41-50);T1(51-60);Tstop(71-80)
C5678901234567890123456789012345678901234567890123456789012345678901234
C       1         2         3         4         5         6         7         8
 4.0E-10  4.0E-8
       1       1         1         1        1        1        0        2        0        0
-1A01   AB1                   0.036 5.12E22.99E8  0.30 1 0                 0
-1AB1   B01                   0.482 5.12E22.99E8  4.00 1 0                 0
-1A10   A11                   0.363 5.12E22.99E8  0.30 1 0                 0
-1A11   A01                   0.036 5.12E22.99E8  3.00 1 0                 0
-1A01   AG1                   0.048 5.06E22.99E8  0.40 1 0                 0
-1AG1   AG2                   0.072 4.86E22.99E8  0.60 1 0                 0
-1AG2   AG3                   0.036 4.60E22.99E8  0.30 1 0                 0
-1AG3   G01                   0.084 4.08E22.99E8  0.70 1 0                 0
-1B01   G02                   0.241 4.71E22.99E8  2.00 1 0                 0
-1A10   G03                   0.241 4.71E22.99E8  2.00 1 0                 0
-1A10   G03   B01   G02                                                    0
 0G01                         50.0                                         1
 0G02         G01                                                          1
 0G03         G01                                                          1
 0A01   AG1                   0.1                                          1
 0AG2   AG3                   0.1                                          1
 0A10   A11                   5.1E2    0.0    0.0                          1
 0AB1   B01                   5.0E4                                        2
BLANK
BLANK
13A10      5.0E+0                   4.0E-9    5.0E+0   40.0E-9      40.0E-9
BLANK
BLANK
BLANK
```

B) Input Data for Base-broadened Tower(Without Ground) for EMTP in Ch.4

```
BEGIN NEW DATA CASE
C   Base-broadened Tower  with  Vertically  applied source far
c   from the the top
C RES(27-32);A(33-38);B(39-44);L(45-50);LINE(51,52);IPUNCH(53,54);IOUT
C (80)
C  AMPLITUDE(11-20);To(31-40);A1(41-50);T1(51-60);Tstop(71-80)
C5678901234567890123456789012345678901234567890123456789012345678901234
C       1         2         3         4         5         6         7         8
 4.0E-10  4.0E-8
       1       1        1       1       1       1         0        2       0       0
-1AT0   A10                    18.08 7.32E22.99E8  150. 1 0                       0
-1A10   A11                    0.060 3.02E22.99E8  0.50 1 0                       0
-1A11   A12                    0.060 2.52E22.99E8  0.50 1 0                       0
-1A12   A13                    0.060 2.17E22.99E8  0.50 1 0                       0
-1A13   A14                    0.060 1.88E22.99E8  0.50 1 0                       0
-1A14   A15                    0.060 1.60E22.99E8  0.50 1 0                       0
-1A15   A16                    0.060 1.29E22.99E8  0.50 1 0                       0
-1A16   G01                    0.120 6.43E12.99E8  1.00 1 0                       0
-1A10   AB1                    0.036 5.95E22.99E8  0.30 1 0                       0
-1AB1   B01                    0.962 5.95E22.99E8  8.00 1 0                       0
-1B01   G02                    0.481 5.54E22.99E8  4.00 1 0                       0
 0G01                          50.0                                               1
 0G02          G01                                                                1
 0A10   AT0                    0.1                                                1
 0A10   A11                    0.1                                                1
 0A12   A13                    0.1                                                1
 0A14   A15                    10.                                                1
 0A16   G01                    20.                                                1
 0AB1   B01                    5.0E4                                              2
BLANK
BLANK
13A10        1.0E+3                  1.0E-9    1.0E+3    50.0E-9      50.0E-9
BLANK
BLANK
BLANK
```

Input Data for Base-broadened Tower(Without Ground) for Line Constant Calculation in EMTP in Ch.4

```
BEGIN NEW DATA CASE
C  SKIN(4-8); RESIS(9-16);IXTYPE(17,18);REACT(19-26);DIA(27-34);
C HORIZ (35-42)
C  VTOWER(43-50);VMID(51-58)
C FREQ. CARD:EARTH RES(1-8); FREQ(8-18);FCAR(19-28);ICPR(30-35)
C ;IZPR (37-42)
C ICAP(44);MODAL(69,70)
LINE CONSTANTS
$ERASE
METRIC
  1  0.5   21.50 4            0.16 79.0   79.0    79.0
BLANK
  1.7E-8  1.953E6          1 000010 010000 0                         1
BLANK
BLANK
$PUNCH
BEGIN NEW DATA CASE
BLANK
```

C) Input Data for Control Building for EMTP in Ch.5

```
BEGIN NEW DATA CASE
C   Control Building  with  Vertically  applied source at the Center
c   far from the the top
C RES(27-32);A(33-38);B(39-44);L(45-50);LINE(51,52);IPUNCH(53,54);IOUT
C (80)
C  AMPLITUDE(11-20);To(31-40);A1(41-50);T1(51-60);Tstop(71-80)
C56789012345678901234567890123456789012345678901234567890123456789012345678901234
C        1         2         3         4         5         6         7         8
4.0E-10  4.0E-8
       1       1         1         1       1       1         0         2      0      0
-1AT0    N01                      7.2E-24.92E23.00E8  0.60 1 0                      0
-1B02    G05                      7.2E-24.27E23.00E8  0.60 1 0                      0
-1A01    B01                      7.2E-24.68E23.00E8  0.60 1 0                      0
-1B01    C01   A01     B01                                                          0
-1C01    D01   A01     B01                                                          0
-1D01    A01   A01     B01                                                          0
-1A01    N01                      5.1E-24.68E23.00E8  0.42 1 0                      0
-1N01    C01                      5.1E-24.68E23.00E8  0.42 1 0                      0
-1B01    N01                      5.1E-24.68E23.00E8  0.42 1 0                      0
-1N01    D01                      5.1E-24.68E23.00E8  0.42 1 0                      0
-1N01    BOM                      2.4E-24.68E23.00E8  0.20 1 0                      0
-1BOM    B02                      2.4E-14.68E23.00E8  2.00 1 0                      0
-1A01    A11                      1.8E-24.61E23.00E8  0.15 1 0                      0
-1A11    A21                      1.8E-24.41E23.00E8  0.15 1 0                      0
-1A21    A31                      1.8E-24.11E23.00E8  0.15 1 0                      0
-1A31    G01                      1.8E-23.47E23.00E8  0.15 1 0                      0
-1B01    B11   A01     A11                                                          0
-1B11    B21   A11     A21                                                          0
-1B21    B31   A21     A31                                                          0
-1B31    G02   A31     G01                                                          0
-1C01    C11   A01     A11                                                          0
-1C11    C21   A11     A21                                                          0
-1C21    C31   A21     A31                                                          0
-1C31    G03   A31     G01                                                          0
-1D01    D11   A01     A11                                                          0
-1D11    D21   A11     A21                                                          0
-1D21    D31   A21     A31                                                          0
-1D31    G04   A31     G01                                                          0
  0A01   A11                      0.1                                               1
  0AT0   A01                      5.1E2    0.0   0.0                                1
  0G01                                  1                                           1
  0G02         G01                                                                  1
  0G03         G01                                                                  1
  0G04         G01                                                                  1
  0G05         G01                                                                  1
  0BOM   B02                      5.0E4                                             2
 BLANK
 BLANK
 13AT0          5.0E+0                   1.0E-9    5.0E+0    40.0E-9    40.0E-9
 BLANK
 BLANK
 BLANK
```

D) Input Data for Actual Tower for EMTP in Ch. 6

```
BEGIN NEW DATA CASE
C   Actual Tower with multi diameter hitting on the top
C RES(27-32);A(33-38);B(39-44);L(45-50) ;ILINE(51,52) ;IPUNCH(53,54)
C ;IOUT(80)
C  AMPLITUDE(11-20);To(31-40);A1(41-50);T1(51-60);Tstop(71-80)
C
567890123456789012345678901234567890123456789012345678901234567890123456789012345
C        1         2         3         4         5         6         7        8
 0.1E-07  20.E-6
        1       1       1       1'      1       1       0       2      0        0
-1AT0   AM0                 0.430 8.11E22.99E8  020. 1 0                        0
-1AM0   A10                 02.80 7.91E22.99E8  130. 1 0                        0
-1A10   A11                 0.430 5.23E22.99E8  020. 1 0                        0
-1A11   A12                 0.430 4.89E22.99E8  020. 1 0                        0
-1A12   A13                 0.430 4.59E22.99E8  020. 1 0                        0
-1A13   A14                 0.430 4.28E22.99E8  020. 1 0                        0
-1A14   A15                 0.430 3.89E22.99E8  020. 1 0                        0
-1A15   G01                 0.430 3.20E22.99E8  020. 1 0                        0
-1A10   AB1                 0.645 7.67E22.99E8  030. 1 0                        0
-1AB1   B01                 04.52 7.67E22.99E8  210. 1 0                        0
-1B01   G02                 02.58 7.26E22.99E8  120. 1 0                        0
 0G01                       50.0                                                1
 0G02           G01                                                             1
 0A10   A11                 0.1                                                 1
 0A12   A13                 0.1                                                 1
 0A14   A15                 10.                                                 1
 0A15   G01                 20.                                                 1
 0AT0   AM0                 5.0E3    0.0  0.0                                   1
 0AB1   B01                 5.0E4                                               2
 BLANK
 BLANK
 13AT0         10.E+3                 0.1E-6     10.E+3    20.0E-6     20.0E-6
 BLANK
 BLANK
 BLANK
```

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AUTHOR

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