STUDY OF EFFECT OF LIGHTNING SURGES ON A POWER SYSTEM BY DIGITAL COMPUTER

BY

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A THESIS

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CERTIFICATE

This is to certify that this work has done by me and it has not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

The effect of lightning surges on East Grid of Bangladesh Power Development Board has been studied by digital computer. The study has been made by using Bewley's Lattice Diagram Method. The lightning surge is represented by a 1/50 wave. Lightning stroke is considered at nodes Sylhet, Siddhirganj, Comilla, Chandraghona and Kaptai. For a single lightning stroke at these nodes there is possibility of voltage build up at some nodes. Most dangerous nodes in the system are Madanhat and Ullon. Possibility of voltage build up increases at some node with repeated lightning stroke. It is observed from surge voltage wave patterns at different nodes that peak value decreases considerably when the system is loaded fully.

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CHAPTER - 1

INTRODUCTION

1.1 Introduction[1],[3]

During switching and similar other processes a system (a circuit or a machine or a transmission line) before coming to a steady state passes through a transition period in which the currents and voltages are not recurring periodic functions of time. The period required for the currents and voltages to adjust themselves to their steady-state modes of variation is called the transient period. During this period in which currents and voltages on a power system undergo a change from one steady state to another, because of lightning, switching operations, short circuits or other causes, surges are set up which travel along the line with the speed of light. These disturbances are partly reflected and partly passed through at any point where there is a change in the line constants, such for example as a change from overhead to underground construction, at a fork in the line or at the terminals. The waves are attenuated in transit and are damped out in a period of time which on any practical line, is very small compared with the time constants of the connected machinery, but during this period some most serious operating problems occur.

1.2 Voltage Transient and Line Surges[2], [3]

There are various ways in which a transmission line may experience transient over voltages. They are of two types (1) internal and (2) external. Internally developed overvoltages are usually caused by a switching operation, either the opening or closing of a circuit breaker. A switching operation produces a sudden change in the circuit conditions, and is accompanied by a transient state which leads from the earlier to the later steady (a.c.) state. The behaviour of the system can be explained with exactness only by means of travelling waves.

With the increase of high - voltage overhead lines the problem of lightning is assuming greater importance, and much damage is done yearly by lightning. There are two main ways in which lightning affects a line: by a direct stroke and by electrostatic induction. A lightning stroke making a direct hit on a power conductor raises its potential enormously; measurements have been made showing that the order of magnitude may be several million volts. There is a great danger that this will flash over the insulators. Voltage caused by sudden changes in the field are induced on conductors in the vicinity of an electric storm. These are of much more frequent occurrence than direct strokes, but they are not so severe.

1.3 Importance of Transient Phenomenon Study[14]

Before the growth of the public utilities into their present enormous proportions with large generating stations and connecting tie lines machine performance was largely judged[8] interms of the steady state characteristics. The emergence of the stability problem gave rise to the analysis of the transient characteristics of machines and was largely responsible for our present knowledge of machine theory. A transient state occurs when the system is changing from one steady state to another. The switching surges rating while the lightning surges may exceed by several tens of times the working voltage, thus seriously affecting the system.

In order to control the operation of a system correctly so as to prevent breakdowns and to design suitable protective and automatic control gear, the engineer must have a clear and detailed picture of all the possible phenomena in a modern power system. The engineer must foresee what will happen to the system as a result of this or that change in its operation. Only then can the engineer determine the required parameters of the equipment and of the protective and automatic gear in order to obtain the best result from the system as a whole and from its constituent parts.

The duration of a transient condition in any system is usually incomparably shorter than that of the normal steady condition. Nevertheless, the overall merit of an electrical system is to a great extent determined by its transient behaviour. The study of transient phenomena in electrical power system is now of special importance because of the increasing use of electronic rectifying devices for automatic and remote control.

As the power system is growing very rapidly and more power needs to be transmitted the system voltage is increasing day by day. More recently, owing to the rise in system operating voltage and to a desire to reduce[4] capital cost by a reduction in system insulation level, the transient voltage arising when long transmission lines are energised and re-energised and due to lightning surges, the means for reducing these transient voltages have become of considerable importance.

1.4 Historical Background

The effect of transient voltages due to switching, lightning stroke, depends on the "wave" parameter of the system. Although a number of methods for calculating switching and lightning transients exist, some are more accurate than others. The methods are Lumped-parameter method, Fourier-transform method, Travelling-wave method and Lattice-diagram method. The earliest method was Schnyder and Bergeron method which was originally a graphical method and this was primarily used in 1928 in Europe for solving hydraulic problems. The method has recently been used in calculating electromagnetic transients using a digital computer.

Almost all power research organisations and power equipments manufacturing companies are working in the field of electromagnetic transients. But Hermann W. Dommel did initial work using computer methods based on Bergeron's method at the Bonneville Power Administration (BPA), USA and the Munich Institute of Technology, Germany, for analyzing transients in power system and electronic circuits and still today he is working at the University of British Columbia, Canada. Secondly, work on electromagnetic transients programme has advanced much by the sincere work of BPA and the information and digital computer programmes are publicly available. Much work is also done at the Hydro-Electric Power Commission of Ontario, Canada. The recent development of sophisticated digital computer programme on transients is the works[11] of Semlyen, Bob Eifrig, Akihiro Ametani, et al.

The latest Electromagnetic Transients Programme (EMTP) is a very sophisticated digital computer programme. The special features are [11] inclusion of synchronous machine dynamics, with special emphasis on subsynchronous resonance (SSR) modelling capability, line constant routine, cable constant routine, dynamic surge arrester model with active (current-limiter) gap, TACS code for analog-computer modelling capability, frequency - dependent model for untransposed transmission lines (Semlyen and Ametani modelling). The smallest of EMTP uses about 7000 cards on IBM 370 computer.

Stability study of Bangladesh Power Grid was made from time to time but only one transient performance study of this grid was done at Bangladesh University of Engineering and Technology by constructing a transient Network Analyser. The main purpose of this study is to investigate the grid under the influence of lightning surges.

1.5 Scope of the Thesis

In a previous study[10], switching and lightning transients were studied on a transient Network Analyser by impinging square wave pulses at certain nodes for lightning transient study. The scope of this thesis is to investigate the effect of lightning surges on the East Grid of Bangladesh Power Development Board by digital computer.

Travelling wave theory and Bewley's lattice-diagram method have been chosen for the study. A lossless, distortion free, single phase representation of east-grid is considered. The study is made over a period of 0 to 10,000 micro seconds. The Grid is studied under the influence of single as well as multiple lightning strokes at different nodes. The main objective of the study is to identify the nodes or points of possible voltage build up due to lightning stroke. This is very important for design, planning and operation of east grid.

CHAPTER - 2

METHODS USED FOR TRANSIENT STUDY

In this chapter a description of different methods used in calculation of electromagnetic transients have been discussed. Bergeron's method is used most extensively. Bewley's Lattice method is a graphical method which uses transmission and reflection coefficients. Transient Network Analyser (TNA) and digital computer are used presently for transient phenomena study but digital computer is gaining popularity as very large and complex systems can be solved economically and very accurately.

2.1. Different Methods Used in Transient Analysis

For the reliable operation of power-system networks it is important to know the condition under which transient over-voltages may be developed within the system and to have the means for their calculation. If this can be done at the design stage, precautions can be taken either to avoid the over-voltages[4] completely or at least to minimise their effects. The calculation of lightning and switching overvoltages has become more and more important with increasing system voltages. Analog and digital computers must be used because of complexity of the systems and their components[5].

Different researchers have solved the transient problems using different methods - Lumped parameter method, Fourier Transform method, Travelling-wave method, Lattice-diagram method. But the most commonly used methods are Bergeron's method and Bewley's

Lattice Diagram method. There are other recent developments but these two methods are widely accepted and extensively used methods.

2.1.1 Bergeron's Method

This method has primarily been used in Europe. It was first applied to hydraulic problems in 1928 and later to electrical problems. It is well suited for digital computers(6). In contrast to the alternative Lattice method for travelling wave phenomena it offers important advantages; for example, no reflection coefficients are necessary. The method has recently been applied to calculation of transients using a digital computer.

A brief outline of Bergeron's Method(7) is given here.

The transmission line equations are:

$$-\frac{\partial e}{\partial x} = L\frac{\partial i}{\partial t} + Ri$$

$$-\frac{\partial i}{\partial x} = C\frac{\partial e}{\partial t} + Ge \qquad \ldots \qquad \ldots \qquad (2.1)$$

where e and i are voltage and current in the line at a distance x and L, C, R and G are respectively the line series inductance, shunt capacitance, series resistance and shunt conductance per unit length.

Bergeron's Method applies to lossless lines where R and G are zero and L and C are independent of frequency.

Subject to these limitations there are relationships between the conditions at each end of the line at time t and at time t - τ which exist independent of the terminating networks.

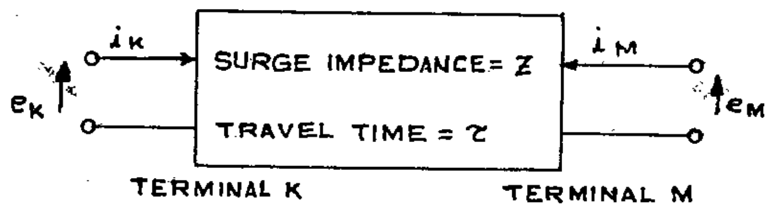


Fig. 2.1 Single Phase Lossless Line.

For the line of Figure 2.1 these relationships are:

$$e_k(t) - Z.i_k(t) = e_m(t - \tau) + Z.i_m(t - \tau)$$
$$e_m(t) - Z.i_m(t) = e_k(t - \tau) + Z.i_k(t - \tau) \qquad \ldots \quad (2.2)$$

Equation 2.2 gives relationships between e and i at both ends of the transmission line which, provided the conditions a travel time earlier are known, enable the transmission line to be replaced by a current source in parallel with a resistance Z. This allows a solution to be obtained for the voltages and currents at time t in the network consisting of the ends of the tranmission lines and the components connected to them. A method for solving this network is described by Dommel.

The quantities $e \pm Z.i$ are known as characteristics and are directly related to the forward and backward travelling waves. In the paper the following nomenclature is used.

$$F_k = e_k + Z.i_k = 2 \times \text{forward travelling wave at end } K,$$
$$B_k = e_k - Z.i_k = 2 \times \text{backward travelling wave at end } K, \qquad \ldots\ldots (2.3)$$

Equation 2.2. can be rewritten:

$$B_K(t) = F_m(t - \tau)$$
$$B_m(t) = F_k(t - \tau) \qquad \ldots \quad \ldots \quad (2.4)$$

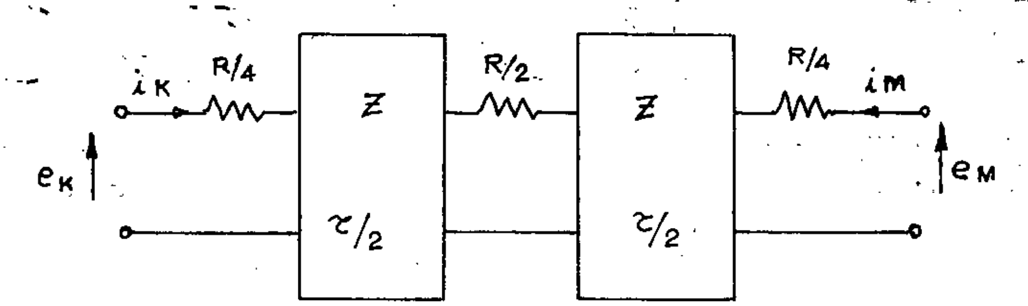


Fig. 2.2 Approximate Model for Line with Series Resistance.

Dommel extends the basic equation (2.4) to include an approximation for series losses. The model used for the transmission lines is shown in Figure 2.2. This results in equations:

$$B_k(t) = \frac{Z}{Z+R/4}\; F_m(t - \tau) + \frac{R/4}{Z+R/4}\; F_k(t - \tau)$$
$$B_m(t) = \frac{Z}{Z+R/4}\; F_k(t - \tau) + \frac{R/4}{Z+R/4}\; F_m(t - \tau) \qquad \ldots \quad \ldots \quad (2.5)$$

In these equations the impedance used in defining the characteristics of equation (2.3) is modified to $(Z+R/4)$. Equation (2.4) is a particular case of equation (2.5) where R is zero. Physically equations (2.4) and (2.5) can be interpreted in terms of impulse responses in the following way:

For the lossless case described by equation (2.4), if an impulse of forward (i.e., into the line) travelling wave is injected at one end at time $t = 0$, then the backward (i.e. out of the line) travelling wave at the other end at time τ is equal to it.

- For the transmission line model with series losses of Figure 2.2 and equation (2.5), if an impulse of forward travelling wave is injected at end m at time $t = 0$, then part of it is transmitted and contributes to $B_k(\tau)$ and part of it is reflected by the resistor at the centre and contributes to $B_m(\tau)$. The responses of B_k and B_m are shown in Figure 2.3.

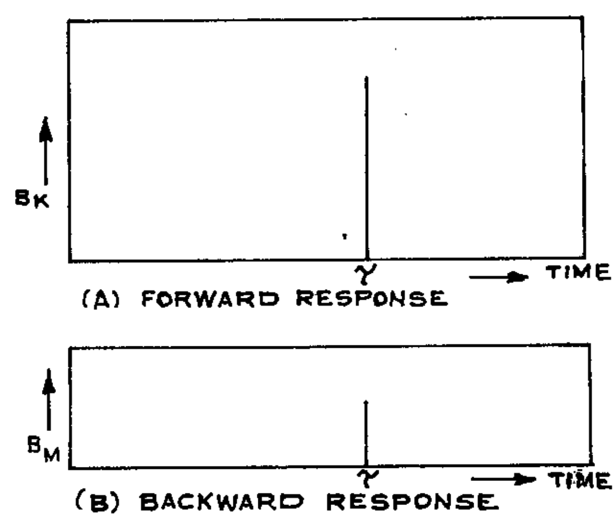


Fig. 2.3 Response Functions for Lumped Resistance Model.

These impulse responses are approximations to the impulse responses of a line with continuously distributed resistance, and frequency dependent resistance and inductance. If the representation of continuously distributed resistance was improved by including a large number of smaller lumped resistances connected by short lossless transmission lines, then the reflection from the resistance in the centre of the line shown in Figure 2.3b would be replaced by many smaller reflections. These reflected pulses would not arrive only at time τ but would occur over a range of time. The reflections from resistances near the sending end would start arriving soon after time zero. The reflections from resistors near the far end would arrive shortly before time 2τ and would be smaller as the pulse will be attenuated as it must pass down the line twice. If the effects of frequency dependence were to be included then the travel time and attenuation of different frequency components would be different and this will further modify the shape of the responses. The principle effect would be, that the pulse of Figure 2.3a would be broadened.

These effects result in responses of the form shown in Figure 2.4. With responses of this form $B_k(t)$ and $B_m(t)$ are no longer determined by $F_k(t - \tau)$, and $F_m(t - \tau)$ alone. However, if F_k and F_m are considered to be made up of a series of impulses of varying amplitude but all of a duration Δt, then B_k and B_m can be found by summing the effects at time t of a number of these impulses. The shape of the responses would only need to be determined once for each line and so could be a complex calculation without greatly increasing the computation time. The summing of the effects of a number of impulses must be

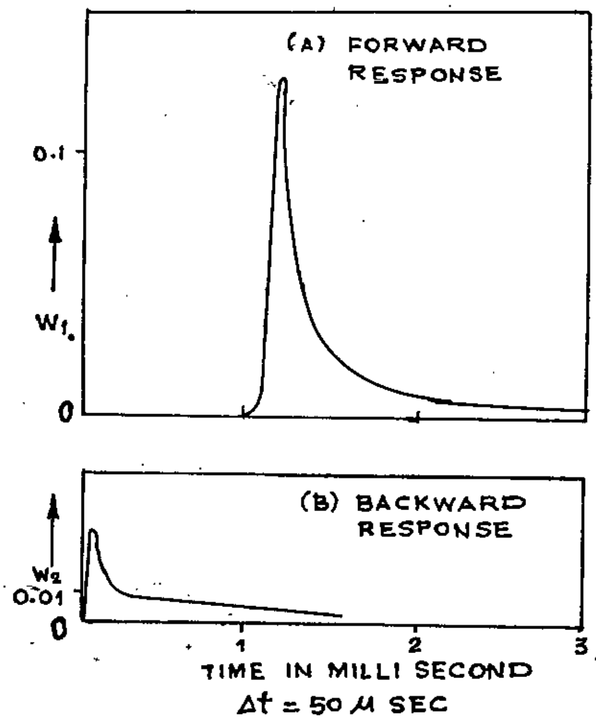


Fig. 2.4 Response Functions of Frequency Dependent 200-Mile Line.

carried out many times, once at each time step, but is only a simple calculation and so should not greatly increase the computation time.

2.1.2 Bewley's Method[(8),(9)]

This is a very convenient diagram devised by Bewley, which shows at a glance the position and direction of motion of every incidence, reflected and transmitted wave on the system at every instant of time. The method may be described as:

If in Fig. 2.5(a) a traveling wave e_f moves from the left to right towards 'a' then upon reaching 'a', a transmitted wave and a reflected wave is produced. These waves can be expressed as follows:

$$e_t = \text{transmitted wave} = \alpha_a e_f \tag{2.6}$$

$$e_r = \text{reflected wave} = \beta_a e_f \tag{2.7}$$

where α_a is the transmission coefficient which is equal to

$$\frac{2R_a}{Z + 2R_a} \tag{2.8}$$

and β_a is the reflection coefficient which is equal to

$$-\frac{Z}{Z + 2R_a} \tag{2.9}$$

So long as the line surge impedances are equal on both sides of the resistor then the transmitted and reflected waves are independent of the direction from which the wave propagates. If on the other hand the line is unsymmetrical with respect to the resistor this statement is untrue. Thus, if the line surge impedance to the left of the resistor is Z and to the right Z', then for a wave moving from the left hand side at the point 'a' the transmission coefficient is

$$\alpha_a = \frac{2RZ'}{RZ+RZ'+ZZ'} \tag{2.10}$$

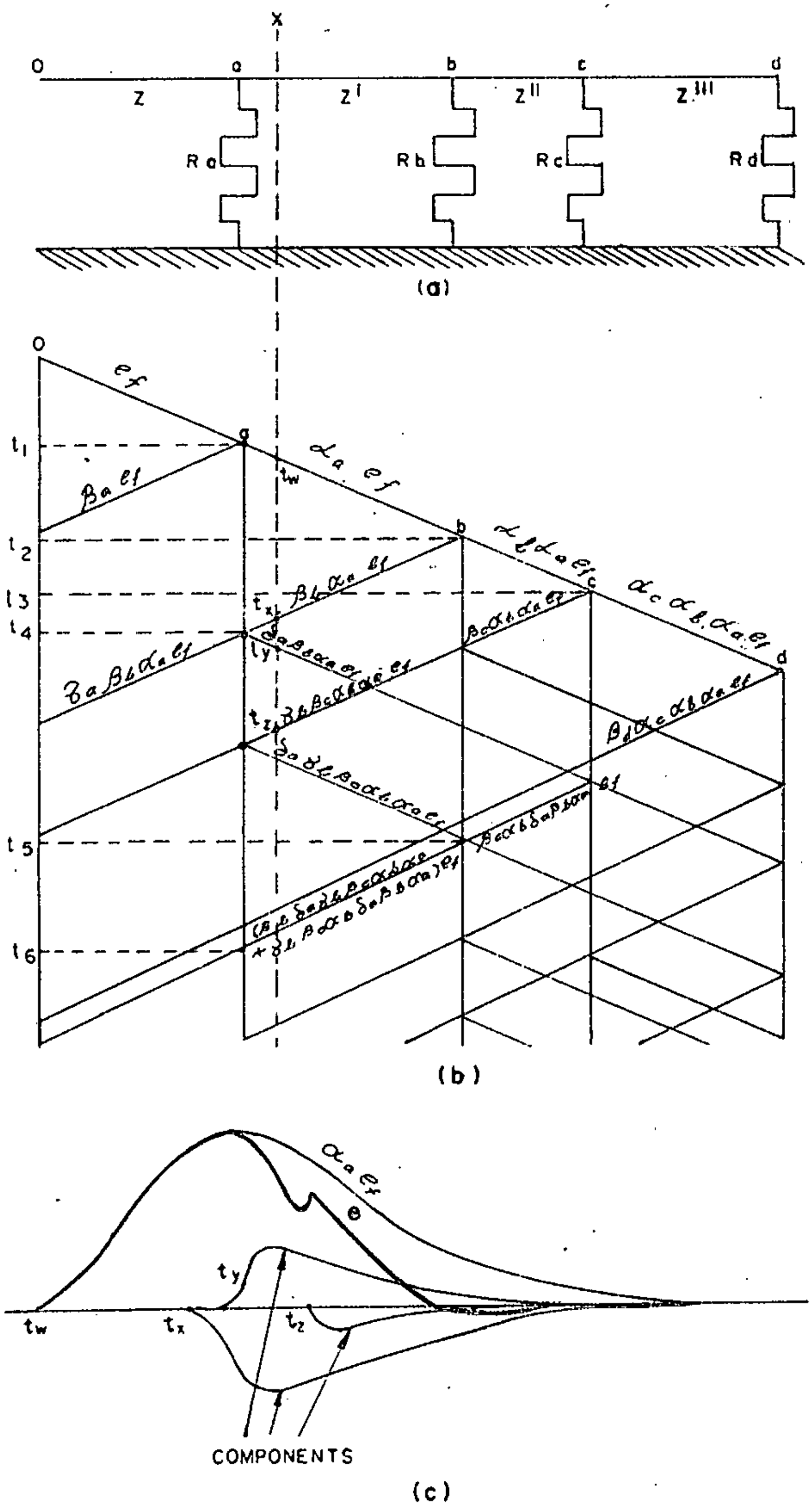


Fig.2.5 Lattice Network, (a) Equivalent circuit of line with several shunt impedances at distributed points. (b) Lattice network for voltage on above circuit. (c) Addition of components from lattice network to give actual voltage at a given point.

and the reflection coefficient is

$$\beta_a = \frac{RZ' - RZ - ZZ'}{RZ + RZ' + ZZ'} \qquad (2.11)$$

For a wave moving from the right to the left, the transmission coefficient, γ_a, is

$$\gamma_a = \frac{2RZ}{RZ'+RZ+ZZ'} \qquad (2.12)$$

and the reflection coefficient, δ_a, is

$$\delta_a = \frac{RZ - RZ' - Z'Z}{RZ' + RZ + Z'Z} \qquad (2.13)$$

When the transmitted wave from 'a' reaches 'b', another reflection and partial transmission occurs. The reflected wave from 'b' is partially transmitted and reflected from 'a'. This continues indefinitely throughout the network until the components have been reduced to zero. By means of the system shown in Fig. 2.5(b) account can be kept of each component not only in magnitude but in time. The horizontal distance represents length along the line and the vertical distance time. The inclined lines are so sloped that the vertical distance represents the time required for the original wave or a reflected component to reach the point designated. Let zero time be the instant at which the travelling wave e_f leaves O. At time t_1 this wave has reached 'a'. The reflected wave from this point is $\beta_a e_f$ which is sloped the opposite direction and is thus indicative of motion in the reverse direction. The transmitted wave from 'a', $\alpha_a e_f$ reaches 'b' at time t_2 when a reflection $\beta_b \alpha_a e_f$ occurs and the wave $\alpha_b \alpha_a e_f$ is transmitted beyond this point. This latter wave reaches 'c' at the time t_3. Each wave whether it be transmitted or reflected has its own transmitted and reflected components. Where two waves coincide as at 'b' for time t_5 where waves from 'a' and 'c' arrive at the same time, the reflected and transmitted waves from this point are added, as has been done for the wave between 'b' and 'a' between t_5 and t_6.

To determine the actual voltage at any point such as 'X' it is necessary to add the different components with their proper time relations as is shown in Fig. 2.5(c). The method is much simpler than this description might convey, as numerical values simplify very greatly the appearance of the steps. In most cases the resistors are equal and equally spaced. If the voltage at any of the resistors is desired, the components of voltage on either one side or the other should be added not the components on both sides.

When 3-phase system is considered, although the basic travelling - wave equations remain unaltered, it is necessary to replace the individual surge impedances by surge-impedance matrix. The manual computation then involved in finding the reflection and refraction coefficients and in calculating the transient voltages and currents in a system of any size is prohibitive, and it becomes necessary to use automatic means of computation, i.e. digital computer.

2.1.3 Transient Network Analyzer

Analog computers, usually named Transient Network Analyzers (TNA), have the advantage that they more or less represent a system physically, but on a miniature scale. They are comparatively easy to design and have been extensively used. They are limited in size, however, and comparatively expensive to build and operate. With the introduction of large and fast digital computers it has become possible to use digital computation instead of analog techniques. Very large systems can now be handled, and it is easy to change the parameters of a system from one calculation to another.

2.2 Comparison of Different Methods

Ideally, the method[4] of calculation used should be capable of representing both lumped and distributed parameters equally well and of faithfully reproducing their variation with frequency. In addition, it should be able to represent the effect of nonlinearities such as those due to surge diverters, magnetic saturation, corona and the circuit-breaker arc. In practice such a method is not easily achieved, and currently used methods represent a compromise in some respect, the particular compromise arrived at being governed by the specific requirements of the user.

Transient overvoltages may be determined by means of a analog computer, such as a transient analyser. In many circumstances, however, it is often found more convenient to use a digital computer and computer programme based on various methods have been and are being developed, some of which are capable of high accuracy. The cost of accuracy is long computation times.

Difficulties inherent in the calculation of transients are not confined to the method alone. The provision of sufficiently accurate and extensive system data also has its problems. For the most accurate methods, full knowledge of parameter variation with frequency is necessary, and at the present time this is not always readily available. Thus, in many cases, the use of more accurate methods available may not be justified economically because of system-data-limitations.

2.2.1 Comparison Between Transient Analyser and Digital Computer[10]

The investment for a Transient Analyzer is almost negligible compared with a high speed digital computer. Yet the digital computer is replacing the Analyzer because the lat.er is restricted to specific problems, whereas the digital computer can be used for a variety of engineering studies. In many cases, the investment in a large computer is justified for the operations it performs in accounting procedures and roll preparation if the engineering use alone does not justify the investment.

In Analyzer study no solution of network or differential equations are required except the physical representation of the system in the miniature. form. Further the Analyzer provides physical observation of the transient phenomena on the oscilloscope-screen and facilitates easy permanent records by photographic means.

The digital computer can not give a continuous history of the transient phenomena but rather a sequence of snapshot pictures at discrete time intervals. In this case unlike the Transient Analyzer numerical answer are printed when the problem is solved and partial answers can be printed during the solution to indicate progress being made towards completing the solution.

There is no doubt that in future, the correct evaluation of switching and lightning surges taking into account complex sources and both voltage and frequency dependent system parameters will be achieved most economically by means of digital computer programs. However, considering the minor investment in Analyzers and the high flexibility of analog methods in the study of electrical transients and cost involved in the preparation of sophisticated and complex digital programs and in their running, the Analyzer methods will be most convenient.

CHAPTER - 3

COMPUTER PROGRAMME DEVELOPMENT FROM BEWLEY'S LATTICE DIAGRAM

Bewley's Lattice Diagram is once again described in this chapter and subsequently equations are written from the graphical representation. Sample computer programme is written from these equations. A description of the grid system under study is given here and required data are tabulated. Mathematical representation of lightning surge and method for calculation of transmission and reflection coefficients for forward and backward waves are shown in the last sections.

3.1 Description of Bewley's Lattice-Diagram Method(4),(8),(12)

The application of the lattice diagram to the calculation of surges on transmission lines and cables is described in many books(8,9) on power systems. In this method, lines and cables are specified by their surge impedances and surge travel times, and the reflected and transmitted voltages and currents at junctions and terminations are calculated by the use of reflection and transmission coefficients, defined for a single-phase system as (fig. 3.1),

$$\beta = \frac{R_e - Z_c}{R_e + Z_c} \qquad \ldots \qquad (3.1)$$

$$\alpha = \frac{2R_e}{R_e + Z_c}$$

where Z_c is the surge impedance of the line or cable on which the wave is travelling and R_e is the effective surge impedance seen by the wave when it reaches the termination or junction.

The surge impedence of a line is calculated as

$$Z_c = \sqrt{L/C}$$

where L is the inductance in henries per unit length of line and C is the capacity in farads per unit length of line. The travel time τ is calculated as

$$\tau = \sqrt{LC}$$

Since the product LC is the same for all overhead lines it follows that the velocity of propagation is also the same. This velocity ($v = \frac{1}{\tau} = \frac{1}{\sqrt{LC}}$) is the same as the velocity of light and for the whole study this is considered as 984 ft. per micro sec. (186000 miles per sec).

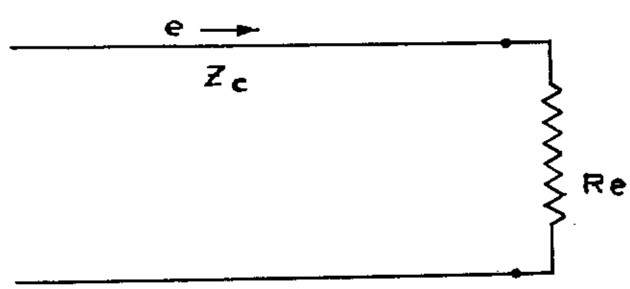


Fig. 3.1 Line Terminated on Resistance R_e.

3.2 Equation Development from Lattice Diagram

Bewley's lattice diagram is a graphical method which shows every incident and reflected wave at every instant of time. But before writing a computer programme mathematical equations must be developed. The equations are formulated in the following way:

Let a forward wave e_f starts at node '0' and travels towards node 1. A part of the wave is transmitted through node 1 with a magnitude of $\alpha_1 e_f$ and a part is reflected as $\beta_1 e_f$. The transmitted wave is then again reflected and transmitted at node 2 and they are $\alpha_1\beta_2 e_f$ and $\alpha_1\alpha_2 e_f$ respectively. And each reflected and transmitted wave gets successive reflection at each node and this continues indefinitely throughout the network until the components have been reduced to zero. To determine the actual voltage build up at any point such as X in Fig. 3.2 it is necessary to add the different components with their proper time relation as shown in Fig. 3.2(c). Equation can be written as:-

$$Ex = \alpha_1 e_f(t_1) + \alpha_1\beta_2 e_f(t_2) + \alpha_1\beta_2\partial_1 e_f(t_3) + \alpha_1\alpha_2\beta_3\gamma_2 e_f(t_4)$$

$$= F_1 e_f(t_1) + F_2 e_f(t_2) + F_3 e_f(t_3) + F_4 e_f(t_4) \quad .... \qquad (3.2)$$

where $F_1 = \alpha_1$, $F_2 = \alpha_1\beta_2$, $F_3 = \alpha_1\beta_2\partial_1$ and $F_4 = \alpha_1\alpha_2\beta_3\gamma_2$ ..(3.2a)

The equation (3.2) can be explained as the original wave e_f is multiplied by a function (eqn. 3.2a) and added together with proper time shift to give the voltage at any point or node in the system. The times t_1, t_2, t_3 and t_4 etc. are the time required for the reflected wave to reach the node where voltage is to be found out. The time can be found out by multiplying velocity of wave (984 ft. per micro sec.) and distance

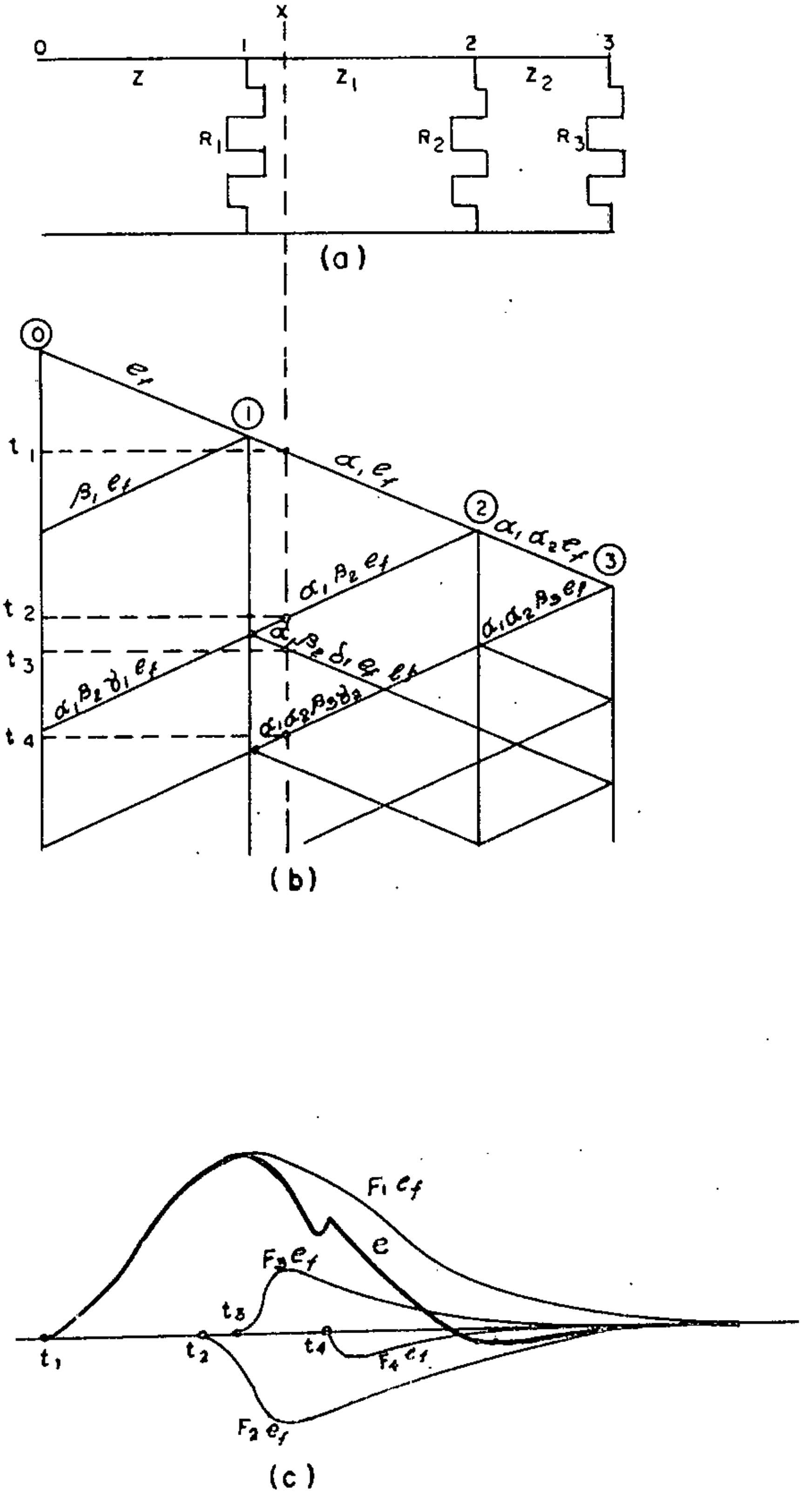


Fig. 3.2 Bewley's Lattice Diagram. (a) Equivalent circuit of line with three shunt impedances at distributed points. (b) Lattice network for voltage on above circuit. (c) Addition of components from lattice network to give actual voltage at a given point X.

travelled. For computer study functions and times are calculated first and then added together using similar equations like equation (3.2) but more lengthy.

3.3. Equations used for Computer Programme

A sample circuit is shown in fig. 3.3. Lightning stroke is considered at node 1. The travelling wave starts from node 1 and is reflected from other nodes. Functions and times are calculated for node 1,2,3,4 and 5. Only one reflection from each node is considered for this study and voltage i.e. functions are calculated just to the right of node.

NODE = 1

Functions:

```
FF(1) = 1.0
FF(2) = B(2)
FF(3) = A(2)*B(3)*G(2)
FF(4) = A(2)*A(3)*B(4)*G(3)*G(2)
FF(5) = A(2)*A(3)*A(4)*B(5)*G(4)*G(3)*G(2)
```

Time :

```
IT(1) = 0
IT(2) = 2*JT(1)
IT(3) = 2*(JT(1)+JT(2))
IT(4) = 2*( JT(1)+JT(2)+JT(3))
IT(5) = 2*( JT(1)+JT(2)+JT(3)+JT(4))
```

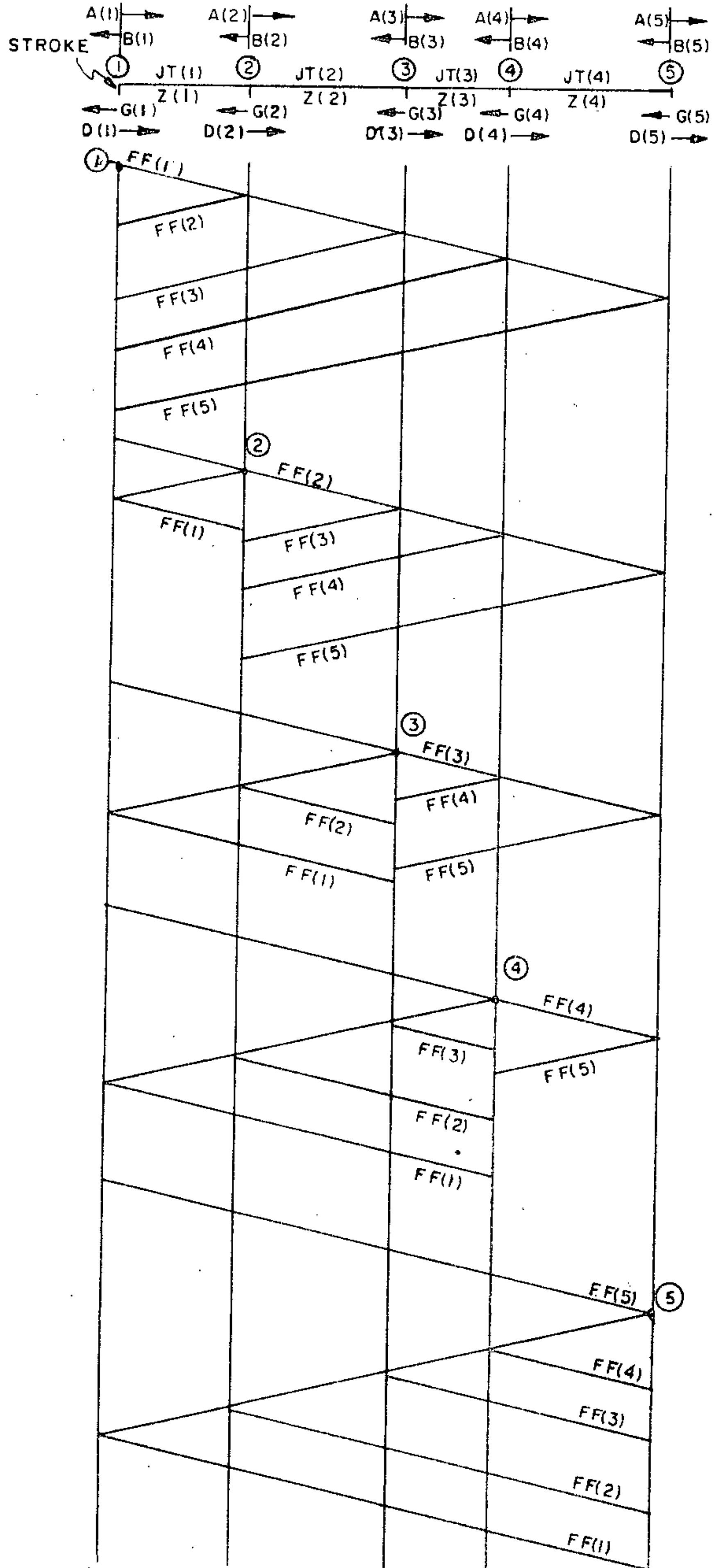


Fig.3.3 Simplified Bewley's Lattice Diagram used for Computer programme.

<u>NODE = 2</u>

```
FF(1) = B(2)*D(1)*A(2)
FF(2) = A(2)
FF(3) = A(2)*B(3)
FF(4) = A(2)*A(3)*D(4)*G(3)
FF(5) = A(2)*A(3)*A(4)*B(5)*G(4)*G(3)

IT(1) = 3*JT(1)
IT(2) = JT(1)
IT(3) = JT(1)+2*JT(2)
IT(4) = JT(1)+2*( JT(2)+JT(3) )
IT(5) = JT(1)+2*( JT(2)+JT(3)+JT(4) )
```

<u>NODE = 3</u>

```
FF(1) = A(2)*B(3)*G(2)*D(1)*A(2)*A(3)
FF(2) =A(2)*B(3)*D(2)*A(3)
FF(3) = A(2)*A(3)
FF(4) = A(2)*A(3)*D(4)
FF(5) = A(2)*A(3)*A(4)*B(5)*G(4)

IT(1) = 3*(JT(1)+JT(2) )
IT(2) = JT(1) + 3*JT(2)
IT(3) = JT(1) + JT(2)
IT(4) = JT(1) + JT(2) + 2*JT(3)
IT(5) = JY(1) + JT(2) + 2*(JT(4)+JT(5) )
```

NODE = 4

FF(1) = A(2)*A(3)*B(4)*G(3)*G(2)*D(1)*A(2)*A(3)*A(4)

FF(2) = A(2)*A(3)*B(4)*G(3)*D(2)*A(3)*A(4)

FF(3) = A(2)*A(3)*B(4)*D(3)*A(4)

FF(4) = A(2)*A(3)*A(4)

FF(5) = A(2)*A(3)*A(4)*B(5)

IT(1) = 3*(JT(1)+JT(2)+JT(3))

IT(2) = JT(1)+3*(JT(2)+JT(3))

IT(3) = JT(1)+JT(2)+3*JT(3)

IT(4) = JT(1)+JT(2)+JT(3)

IT(5) = JT(1)+JT(2)+JT(3)+2*JT(4)

NODE = 5

FF(1) = A(2)*A(3)*A(4)*B(5)*G(4)*G(3)*G(2)*D(1)*A(2)*A(3)*A(4)*A(5)

FF(2) =A(2)*A(3)*A(4)*B(5)*G(4)*G(3)*D(2)*A(3)*A(4)*A(5)

FF(3) = A(2)*A(3)*A(4)*B(5)*G(4)*D(3)*A(4)*A(5)

FF(4) = A(2)*A(3)*A(4)*B(5)*D(4)*A(5)

FF(5) = A(2)*A(3)*A(4)*A(5)

IT(1) = 3*(JT(1)+JT(2)+JT(3)+JT(4))

IT(2) = JT(1)+3*(JT(2)+JT(3)+JT(4))

IT(3) = JT(1)+JT(2)+3*(JT(3)+JT(4))

IT(4) = JT(1)+JT(2)+JT(3)+3*JT(4)

IT(5) = JT(1)+JT(2)+JT(3)+JT(4)

Now let us write the programme for finding voltage at node 2 for a lightning stroke at node 1.

```
C       PROGRAMME NO. 1
C       CALCULATION OF VOLTAGE AT NODE 2 FOR SINGLE STROKE AT NODE 1
        DIMENSION A(5),B(5),G(5),D(5),JT(4),FF(5),IT(5),F(4000)
        READ (1,10)  (A(I), I = 1,5)
        READ (1,10) (B(I), I = 1,5)
        READ (1,10) ( G(I), I = 1,5)
        READ (1,10) ( D(I), I = 1,5)
        READ (1,11) ( JT(I), I = 1,4)
10      FORMAT (5F10.5)
11      FORMAT (4I6)
        FF(1) = B(2)*D(1)*A(2)
        FF(2) = A(2)
        FF(3) = FF(2)*G(3)
        FF(4) = A(2)*A(3)*B(4)*G(3)
        FF(5) = FF(4)*A(4)*B(5)*G(4)/B(4)
        IT(2) = JT(1)
        IT(1) = 3*IT(2)
        IT(3) = IT(1) + 2*JT(2)
        DO 20 I = 4,5
20      IT(I) = IT(I-1) + 2*JT(I-1)
        AAA = 0.014194
        BBB = 6.073014
        V0  = 1.016671
        DO 15 I = 1,4000
15      F(I) = 0.0
        DO 30 K = 1,5
        N  = IT(K)
        DO 30 J = 1,300
```

```
      SS = J
      X  = - AAA*SS
      Y  = - BBB*SS
      EXX = EXP(X)
      EXY = 0.0
      IF(J.LT.7) EXY = EXP(Y)
      V  = VO*(EXX-EXY)
      M = N + J
30    F(M) = F(M) + V*FF(K)
      WRITE (3,35)
35    FORMAT (1H1, 50X, 'TRANSIENT VOLTAGE AT NODE TWO'//)
      WRITE (3,36) (I,F(I), I = 1,4000, 2)
36    FORMAT ( 9(I5, F9.4) )
      END
```

Voltage for each node can be found like this. For voltage calculation at different nodes a single programme has been developed.

3.4 The System Under Study

The East Grid of Bangladesh Power Development Board has been taken for study. The single line diagram is shown in Fig. 3.4. It has five major power stations at Kaptai (Hydro-electric), Siddhirganj(steam),Ghorasal (steam), Ashuganj(steam) and Shahibazar (gas-turbine). The system has double circuit 132 KV line connecting all major power stations. The total length (132 KV) of the system (1979) is 560 miles. The East Grid covers about eight districts and the main load centres. About seventy-five percent of system maximum demand and energy is despatched through this grid. The system under study is shown in Fig. 3.5.

3.4.1 Data Calculation

The data for the system has been calculated from per unit value to corresponding actual value. The data originally available was in p.u. values at base value of 132 KV and 100 MVA. The surge impedances are calculated and shown in Table 1. For detailed calculation refer to Appendix-B.

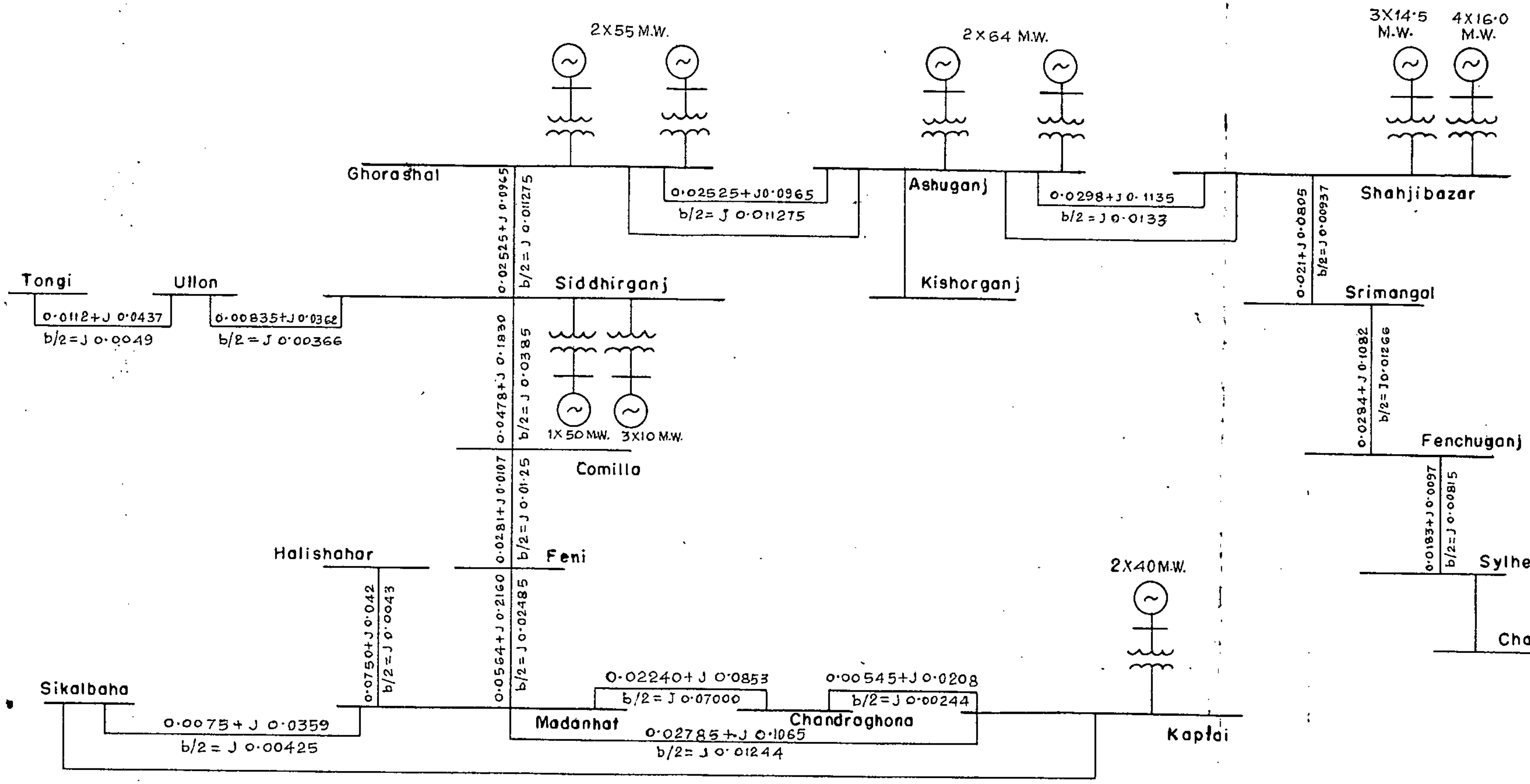
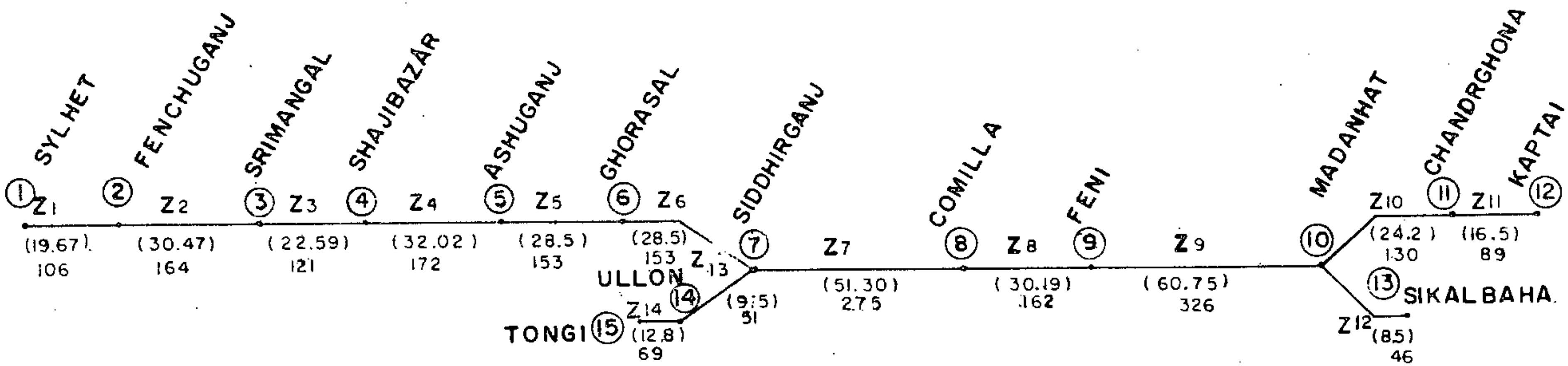


FIG. 3·4 EAST GRID OF BANGLADESH POWER DEVELOPMENT BOARD

One Line Impedance Diagram
Base 100 MVA. 132 KV. Date April 21, 1975.



INDEX

Z SURGE IMPEDANCE OF THE SECTION

(19.67) MILAGE OF SECTION

106 TRAVEL TIME FOR THE SECTION IN μ SECOND.

Fig.3.5 Single line representation of East Grid used for Computer programme.

TABLE - 1

TRANSMISSION LINE DATA

Sections	Length in miles	Line contents on 100 VA, 132 V base			Surge Impedance in ohm	Travel time in micro seconds
		R in ohm	L in mh	C in μF	$Z = \sqrt{L/C}$	
Sylhet - Fenchuganj	19.67	3.20	38.6	0.298	359.90304	106
Fenchuganj-Srimangal	30.47	4.94	60.0	0.464	359.59746	164
Srimangal-Shahjibazar	22.59	6.66	44.6	0.344	360.07104	121
Shahjibazar-Ashuganj	32.02	5.20	62.8	0.490	357.99896	172
Ashuganj-Ghorasal	28.50	4.40	53.3	0.412	360.35310	153
Ghorasal-Siddhirganj	28.50	4.40	53.5	0.412	360.35310	153
Siddhirganj-Ullon	9.50	1.45	20.8	0.134	393.98461	51
Ullon-Tongi	12.80	1.95	24.2	0.180	366.66666	69
Siddhirganj-Comilla	51.30	8.30	101.3	1.220	288.15410	275
Comilla-Feni	30.19	4.90	59.5	0.454	362.01831	162
Feni-Madanhat	60.75	9.30	119.0	0.910	361.62028	326
Madanhat-Chandraghona	24.20	3.90	47.3	0.366	359.49265	130
Chandraghona-Kaptai	16.50	0.95	11.5	0.090	357.46016	89
Madanhat-Sikalbaha	8.50	1.31	19.9	0.156	357.61995	46

3.4.2 Mathematical Representation of Lightning Surge Wave

Studies of transient disturbances on a transmission system have shown that lightning strokes[13] and switching operations are followed by a travelling wave of a steep wave front. When a voltage wave of this type reaches a power transformer it causes an unequal stress[4] distribution along its windings and may lead to breakdown of the insulation system. It has, therefore, become necessary to study the insulation behaviour under impulse voltages.

An impulse voltage is a undirectional voltage which rises rapidly to a maximum value and then decays slowly to zero. The wave shape is generally defined in terms of time t_1 and t_2 in microseconds, where t_1 is the time taken by the voltage wave to reach its peak value and t_2 is the total time from the start of the wave to the instant when it has declined to one-half of the peak value. The wave is then referred to as a t_1/t_2 wave (Fig. 3.6) and according to B.S. 923 a 1/50 microsecond wave is the standard wave. The general equation of an impulse voltage

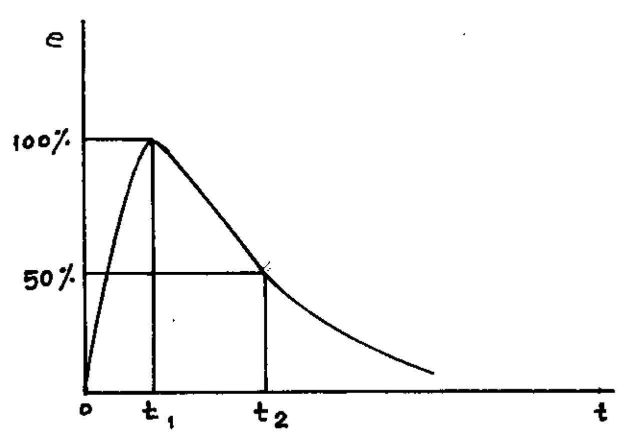


Fig. 3.6 Nature of a lightning discharge.

is given by -

$$V(t) = V\left[\exp\left(\frac{-t}{R_2 C_1}\right) - \exp\left(\frac{-t}{R_1 C_2}\right)\right]$$

$$= V(\exp^{-at} - \exp^{-bt})$$

The value of V, a and b for a 1/50 wave has been found by trial and error method and equation is given by -

$$V(t) = 1.016671\,(e^{-0.014194t} - e^{-6.073014t}) \quad \ldots \quad (3.3)$$

For procedure for calculation refer to Appendix-C.

3.5 Calculation of Transmission and Reflection Co-efficients

The calculation of transmission and reflection constants α, β, γ and ∂ have been done by Programme no.1 and shown in Appendix-A.

3.5.1 Propagation of Surges in a Line Terminated by a Finite Impedance(2)

Suppose that a travelling wave (E,i) moves along a line of surge impedance (Z) and meets a termination of resistance R (Fig. 3.7). If R is not equal to Z, the end of the line can not have a voltage E and current i, since E/i = Z. There is therefore a disturbance which produces a reflected wave (E',i') moving towards the left.

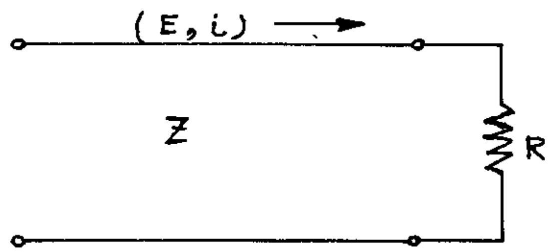


Fig. 3.7 Line Terminated on a Resistance R.

The following relations exist:

$E = iZ,$

$E' = -i'Z$

The total voltage at the end is $E + E'$ and the total current is $i + i'$, so that $E + E' = R(i + i')$.

These equations give

$Z(i-i') = R(i+i')$

So that $i' = ((Z-R) / (Z+R))i$ ... ... (3.4a)

and $E' = -i'Z = ((R-Z) / (Z+R)) E$ ... ... (3.4b)

The total current and voltage are

$i+i' = (2 Z/ (Z+R)) i$ ... ... (3.5a)

and $E+E' = (2R/ (Z+R)) E$ ... ... (3.5b)

If the line is open at the end, $R = \infty$ so that the total current is zero and the total voltage is 2E.

If the line is shorted at the end, $R = 0$, so that the current is doubled and the voltage drops to zero.

The case for a finite resistance termination is given by equations (3.4) and (3.5), when the termination is not a pure resistance, the result is still given by these equations but they must be modified by the terminated impedance. A load in the line may also be treated as a special case of "termination" at a given point of the system.

3.5.2 Surges at the Junction of two Lines

Figure 3.8 shows the case of two lines of surge impedances Z_A and Z_B. A wave (E,i) travels along the left-hand line and meets the junction. So far as a travelling wave is concerned the righthand line can be considered to have an impedance Z_B, so that the case is the same as that shown in 3.7 provided Z is replaced by Z_A and R by Z_B.

The reflected wave is thus (E', i') where

$$i' = ((Z_A - Z_B)/(Z_A + Z_B))i \qquad \ldots \qquad (3.6a)$$

and $$E' = ((Z_B - Z_A)/(Z_A + Z_B))E \qquad \ldots \qquad (3.6b)$$

The transmitted wave must clearly have a voltage equal to the total voltage at the junction and a current equal to the total. Thus the transmitted wave is (E", i") where

$$i'' = i + i' = (2Z_A \;/\; (Z_A + Z_B))\; i \qquad \ldots \qquad (3.7a)$$

and $$E'' = E + E' = (2Z_B \;/\; (Z_A + Z_B))\; E \qquad \ldots \qquad (3.7b)$$

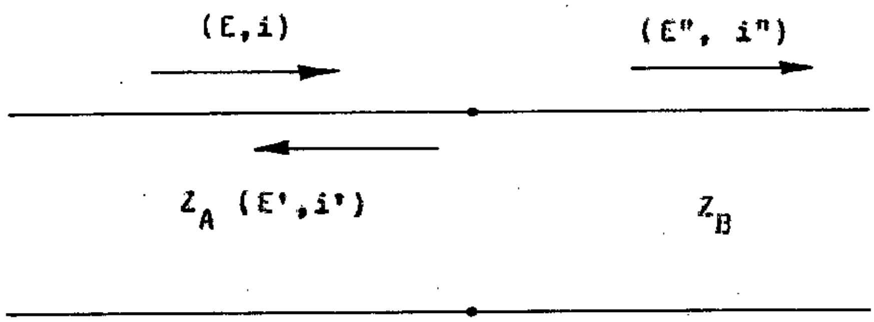


Fig. 3.8 Junction of 2 lines.

The reflected and transmitted waves at a point where a line forks (i.e. Junction of three lines). Fig. 3.9 represents the arrangement schematically. The surge impedances are Z, Z_1, and Z_2 respectively.

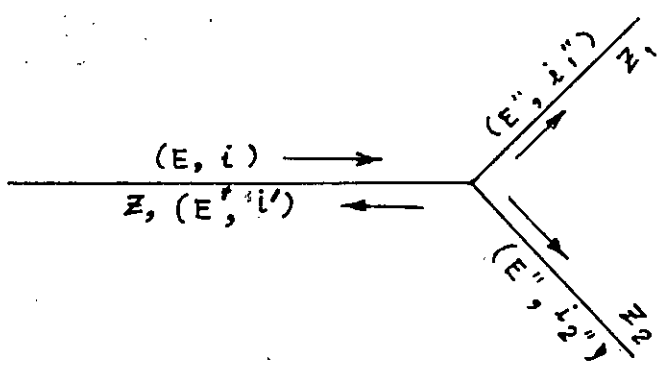


Fig. 3.9 Travelling waves at a junction of 3 lines.

Let the incident wave be (E,i) travelling to the right, the reflected wave (E',i') travelling to the left, and the transmitted waves (E", i_1"), and (E", i_2") travelling towards the right. The transmitted waves clearly have the same voltage as they are in parallel. The relations are given by equations (3.8).

$$E = iZ$$
$$E' = -i'Z$$
$$E'' = i_1'' Z_1$$
$$E'' = i_2'' Z_2 \qquad \ldots \qquad \ldots \qquad (3.8)$$

The current at the fork must be equal to the current leaving, so that

$$i + i' = i_1'' + i_2'' \qquad \ldots \qquad \ldots \qquad (3.9)$$

The voltage at the junction is

$$E + E' = E'' \qquad \ldots \qquad \ldots \qquad (3.10)$$

These six equations are sufficient to find E', E'', i, i', i_1'', and i_2'' for an incident wave of magnitude E. Substituting for the currents in terms of the voltage, we see that equation (3.9) becomes

$$E - E' = E''Z\,(1/Z_1 + 1/Z_2)$$

adding this to equation (3.10) we get

$$2E = E''(1 + Z/Z_1 + Z/Z_2).$$

So that the voltage at the fork is

$$E'' = 2E/(1 + Z/Z_1 + Z/Z_2) = 2E(1/Z)/(1/Z + 1/Z_1 + 1/Z_2) \quad \ldots \; (3.11)$$

The transmitted current are

$$i_1'' = E'' / Z_1 \text{ and } i_2'' = E'' / Z_2,$$

whilst the incident current is

$$i = E/Z.$$

The reflected voltage is

$$E' = E'' - E = \frac{E(1/Z - 1/Z_1 - 1/Z_2)}{(1/Z + 1/Z_1 + 1/Z_2)} \qquad \ldots \qquad (3.12)$$

and the current is

$i' = - E'/Z$. It is seen that the reflected voltage wave is zero when

$$i/Z = (1/Z_1 + i/Z_2),$$

i.e. then the parallel combination of the surge impedances of the outgoing lines at the fork is equal to the surge impedances of the line along which the incident wave travels.

CHAPTER - 4

COMPUTER STUDIES AND THEIR RESULTS

Description of different programmes and their results are shown in this chapter. First the value of transmission and reflection coefficients for forward and backward moving waves for no load connected are found out. Voltage wave at different nodes for stroke at other nodes are found and curves are drawn. For the study the system is considered as lossless and distortion free. Single reflection is considered from each node and output print is taken at alternate micro-second. Study is made from 4,000 micro-seconds to 10,000 micro-seconds but results are usually shown upto 4,000 micro-seconds. The graphs are first plotted in large graph papers and then reduced twice by Pentograph and Xerox photocopy machine to the desired size. The computer programmes are written in FORTRAN-IV language and run in IBM-360 computer.

4.1 Representation of Input Lightning Surge Wave Pulse

The lightning surge is represented by a 1/50 wave (Fig. 4.1) which according to the standard specified in B.S. 923 is the standard wave.

4.2 Calculation of Transmission and Reflection Co-efficients

The transmission and reflection coefficients are found for forward moving and backward moving waves. The programme is shown in Appendix-A (Programme-1). The nomenculture used for computer study is:

Alpha = A = transmission coefficient for forward moving wave.

Beta = B = reflection coefficient for forward moving wave.

Gamma = G = transmission coefficient for backward moving wave.

Delta = D = reflection coefficient for backward moving wave.

4.3 Surge Voltage Wave at Node 2(Fenchuganj) for Stroke at Node 1(Sylhet).

First study is made for voltage build up at node 2(Fenchuganj) for stroke at node 1(Sylhet). Three sets of results are obtained for no load condition, load at node 6(Ghorasal) and load at node 12(Kaptai) condition. Resistive loads of 100 ohm (174 MVA) at Ghorasal and 80 ohm (217.8 MVA) at Kaptai are considered one at a time and the results are shown in Fig. 4.2. through fig. 4.4. Each figure contains three curves where effect of considering only one reflection from each node, considering 4 successive reflections from adjacent two nodes and effect of two strokes of 500 micro-seconds interval at Sylhet are shown. The programme may be seen in Appendix-A (Programme No.2).

4.3.1 Surge Voltage Wave at all Nodes for Single Stroke at Node 1(Sylhet)

Investigation is made for possible voltage build up at all nodes of the system for a single stroke at node 1(Sylhet). A single programme is written (refer Appendix-A, Programme No.3) for this and flow diagram is shown in Fig. 4.22. First computer print out is taken for 4,000 micro-seconds for surge voltage wave at each node, but later voltage wave readings are taken for only those nodes where build up possibility exist. Three sets of data are fed i.e. no-load condition, load at node 6(Ghoresal) and load at node 12(Kaptai) condition. The surge voltage wave patterns are drawn and shown in Fig. 4.5 to Fig. 4.9 and Fig. 4.18.

4.4 Surge Voltage Wave at all Nodes for Single Stroke at Node 12(Kaptai)

A computer programme is developed (refer Appendix-A, Programme no.4) for finding surge voltage wave at different nodes for single stroke at node 12(Kaptai). In order to save computer time, check programme is run, where only functions and corresponding times (refer page 25., Chapter 3) are printed. Finally voltage wave patterns are drawn using programme no.6. Study is made for no load condition, load connected at node 6(Ghorasal) and load connected at node 12(Kaptai) condition. Wave shapes are drawn only for nodes where possibility of appreciable voltage build-up exist and are shown in Fig. 4.12.

4.5 Surge Voltage wave at Adjacent Nodes for Single Stroke at Nodes 11(Chandraghona), 7(Siddhirganj) and 8(Comilla)

Functions and times are calculated for adjacent nodes for stroke at node 11(Chandraghona), 7(Siddhirganj) and 8(Comilla) by programme no.5. The functions and time are checked whether any possibility of voltage build up exist and then these data are fed to programme no.6. The output is the surge voltage wave shape data and these data are plotted and shown in Figs. 4.11, 4.13 and 4.14. This study is also made for no load condition, load at node 6(Ghorasal), load at node 12(Kaptai) condition.

4.6 Repeated Lightning Stroke of 500 and 1500 Micro-seconds Interval

Study is also made for multiple stroke, as one third of power system surges are multiple[8] and the maximum number of components recorded is 10. The time interval between strokes varies between 0.0005 and 0.5 seconds. So, two strokes of same magnitude (1 p.u.) and of 500 and 1500 micro-seconds interval are considered to study the effect of multiple stroke. From the values of function and time at different nodes (for stroke at other nodes) it could easily be estimated whether the two stroke would add up. Then the data is fed in programme no.6 and surge voltage patterns are drawn.

4.7 Study of Loaded System

Usually surge voltage peaks are damped when the system is loaded. For this investigation, loads of different values (in accordance with actual system load) are connected to all nodes of the system. The values of resistive load at different nodes, are shown in Table 2.

4.8 Study with Artificial Reactor at Node 14(Ullon)

An artificial reactor of 4 milli-henry is considered in line between Ullon and Tongi and with this added value, α, β, γ and ∂ for node 14(Ullon) are found out. With this new value, surge voltage wave at Ullon for stroke at different nodes is found out.

TABLE - 2

Value of resistive load

Node	Value of resistive load in ohm	Value of resistive load in MVA	Value of coefficients Alpha	Beta	Gamma	Delta
1 (Sylhet)	3030	5.75	0.0	0.0	1.7877	0.7877
2 (Fenchuganj)	8066	2.16	0.9472	-0.0528	0.9438	-0.4259
3 (Srimangal)	3095	5.63	0.9472	-0.0528	0.9438	-0.4259
4 (Shejibazar)	6050	2.88	0.9605	-0.0314	0.9720	-0.0279
5 (Ashuganj)	1908	9.13	0.9190	-0.0809	0.9090	-0.0909
6 (Ghorasal)	825	21.13	0.8197	-0.1803	0.8197	-0.1803
7 (Siddhirganj)	174	100.25	0.3817	-0.6180	0.4776	-0.5224
8 (Comilla)	955	18.25	0.9534	-0.0465	0.7588	-0.2411
9 (Feni)	6050	2.88	0.9704	-0.0296	0.9715	-0.0285
10 (Madanhat)	603	28.88	0.5529	-0.4471	0.5563	-0.4437
11 (Chandraghona)	1467	11.88	0.8885	-0.1114	0.8936	-0.1064
12 (Kaptai)	5808	3.00	1.8840	0.8840	0.0	0.0
13 (Sikalbaha)	4356	4.00	1.8483	0.8483	0.0	0.0
14 (Ullon)	286	61.00	0.5654	-0.4346	0.6075	-0.3925
15 (Tongi)	715	24.38	1.3320	0.3320	0.0	0.0

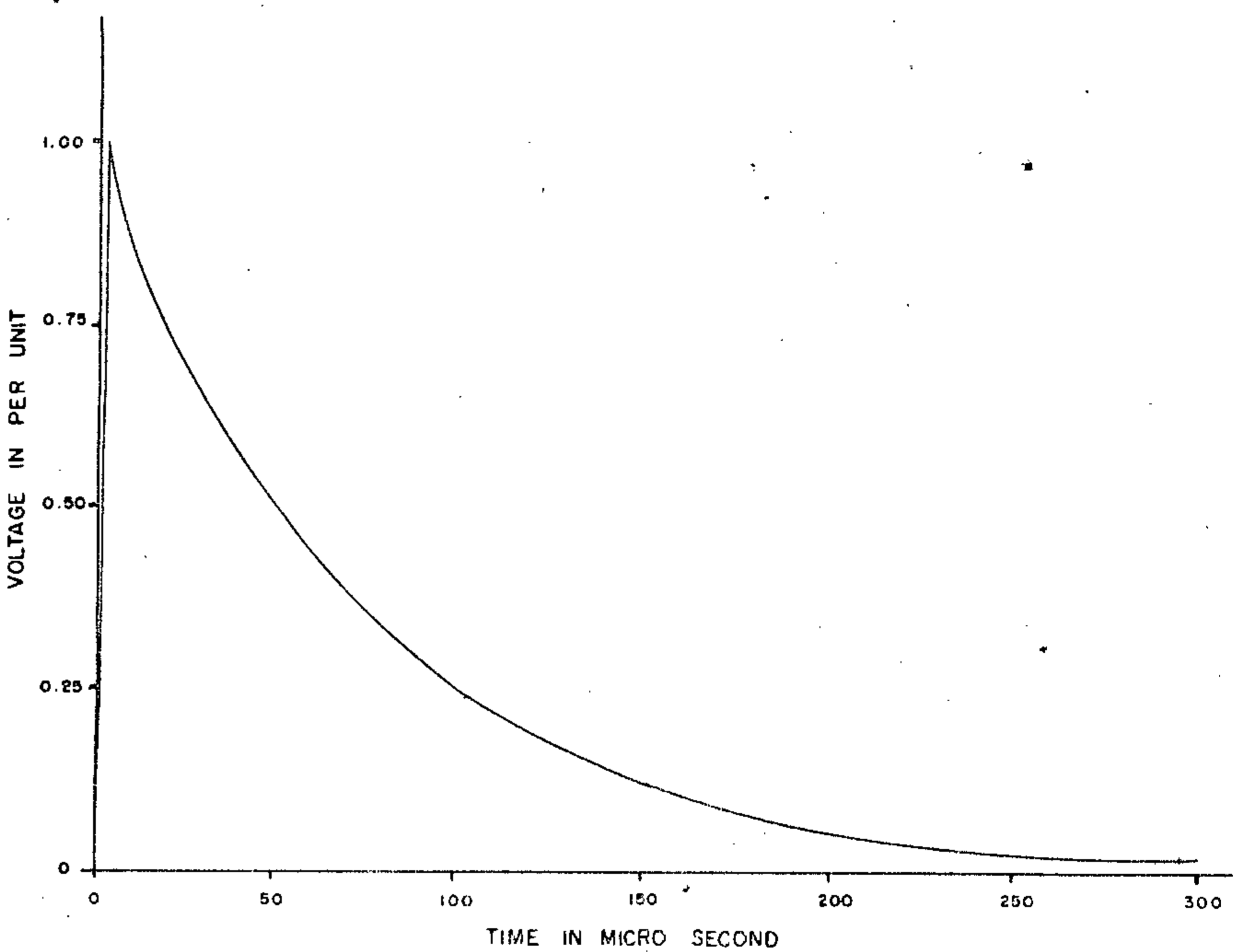
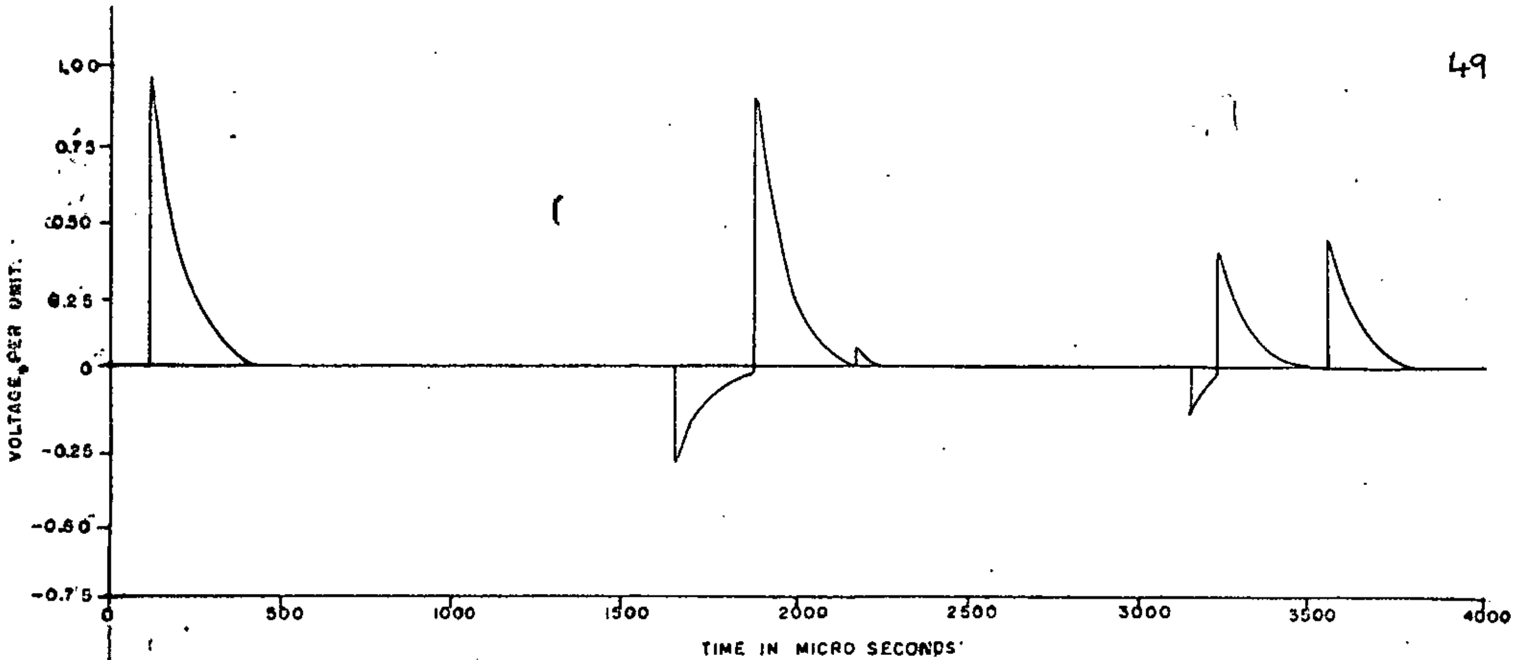
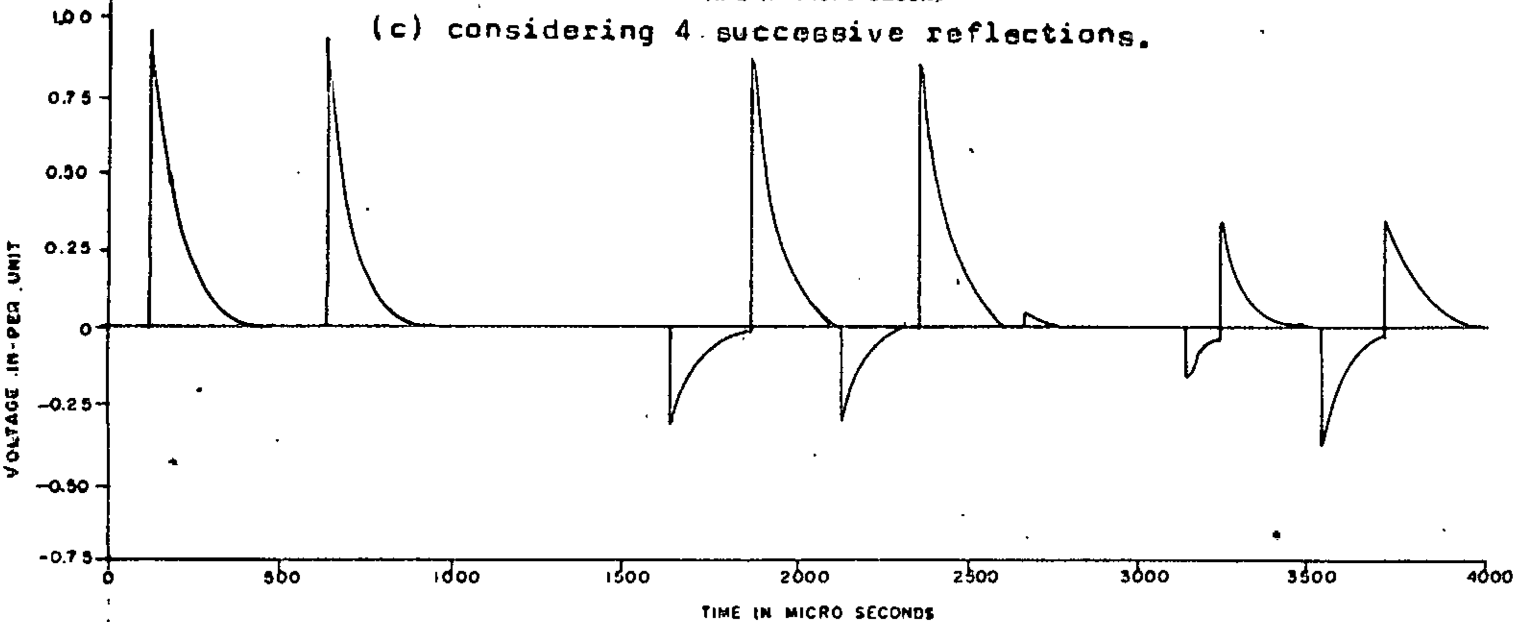


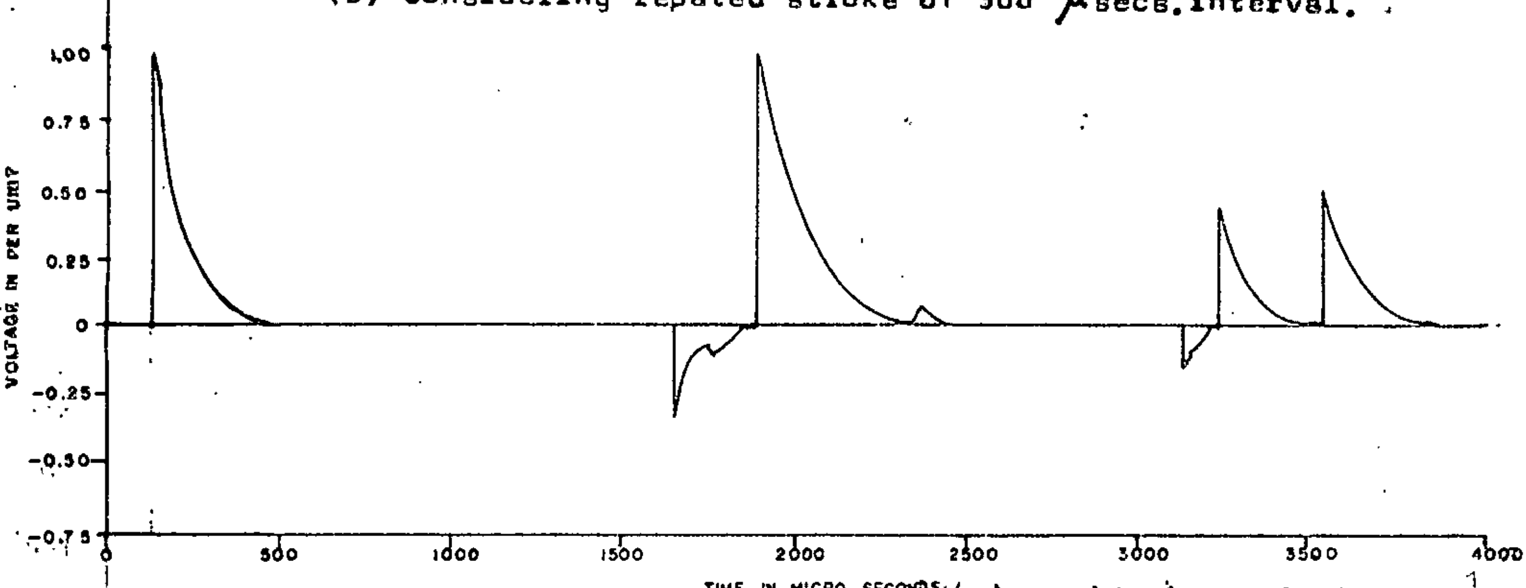
FIG. 4.1 INPUT LIGHTNING SURGE WAVE



(c) considering 4 successive reflections.

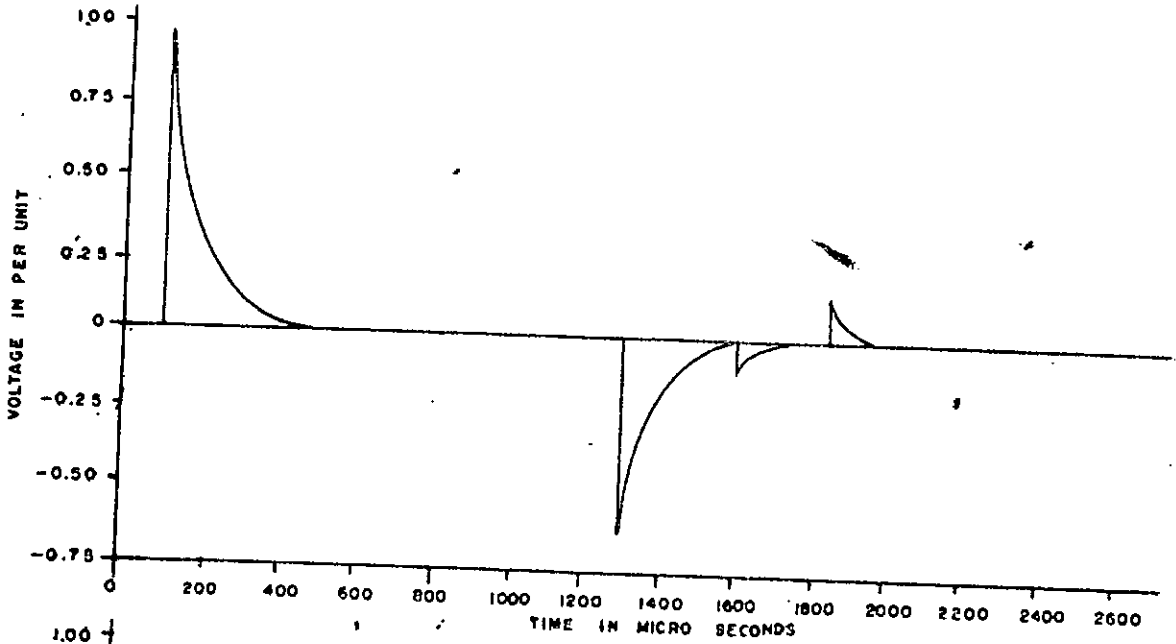


(b) Considering repated stroke of 500 μsecs.interval.

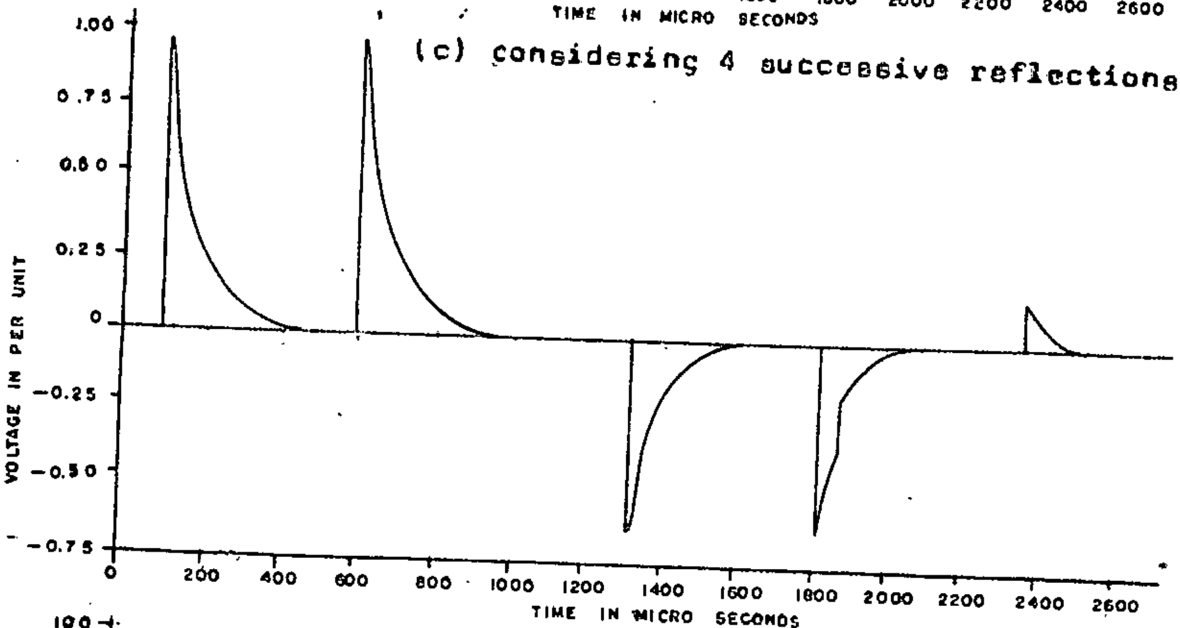


(a) considering only 1 reflectio

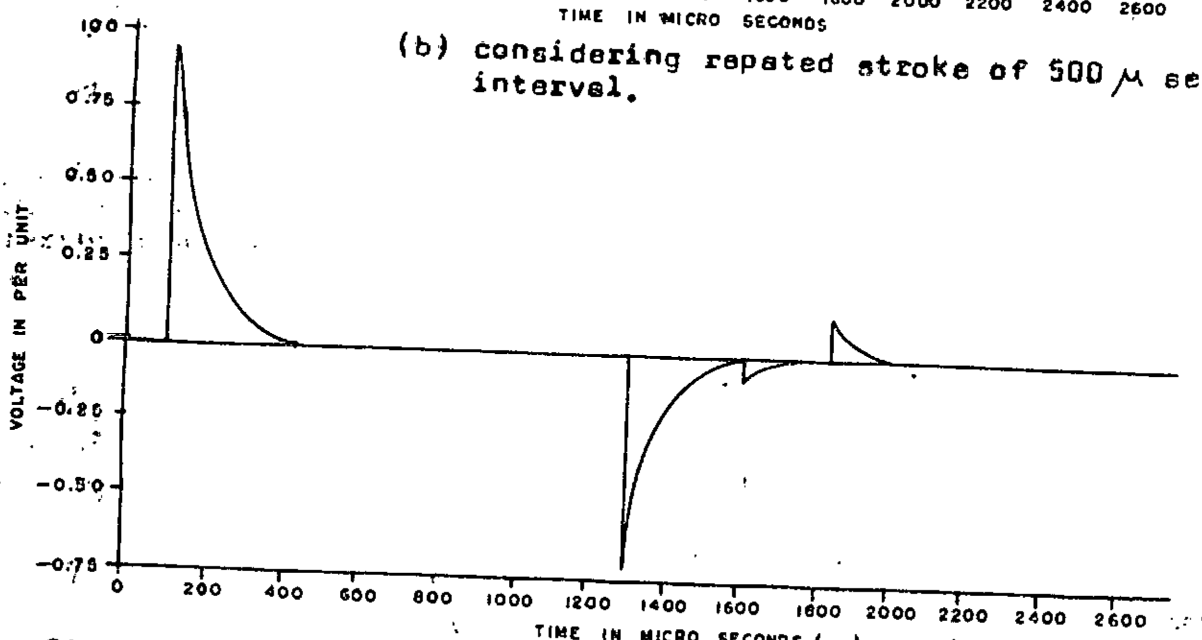
Fig. 4.2 Surge voltage wave at node 2 (Fenchuganj) for lightning stroke at node 1(Sylhet) under no load considering different conditions.



(c) considering 4 successive reflections

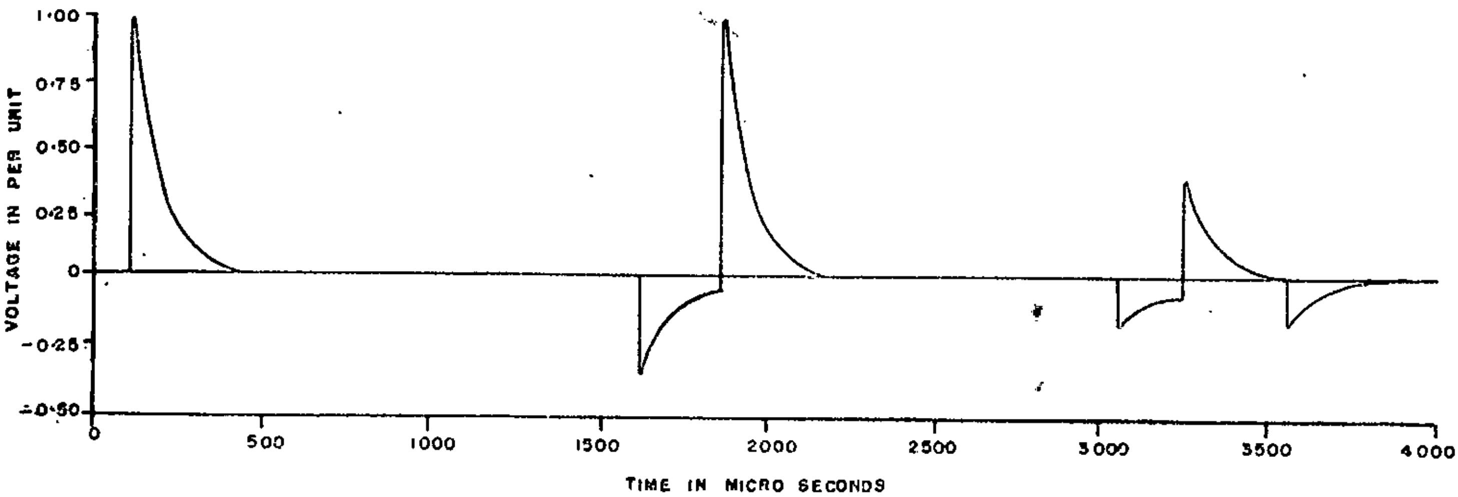


(b) considering repated stroke of 500 μ secs. interval.

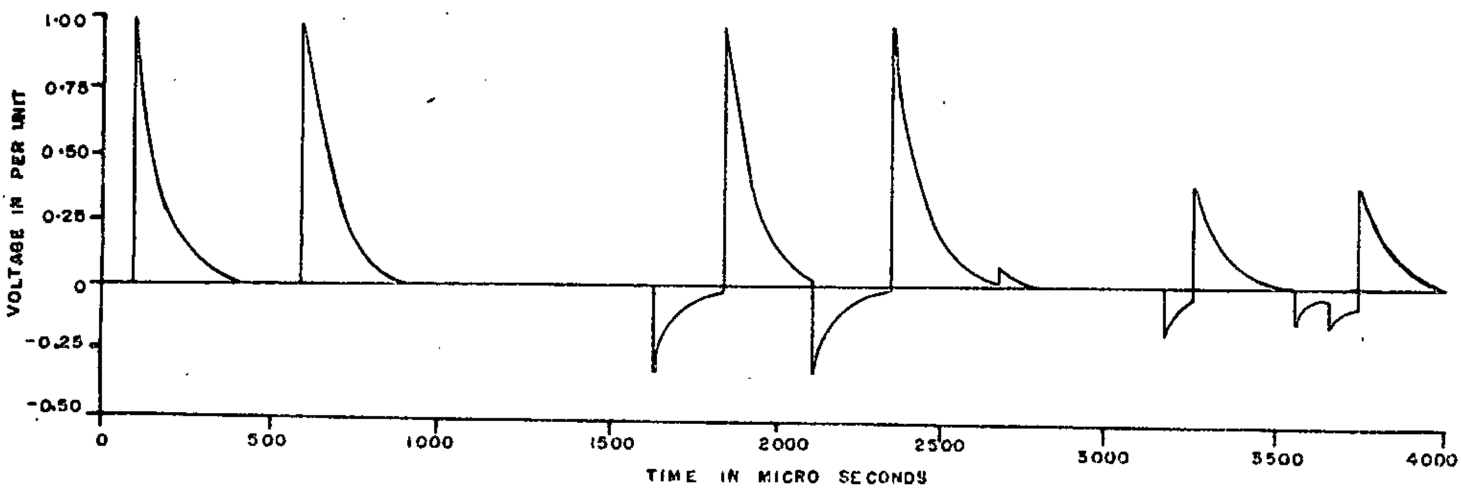


(a) considering only 1 reflection.

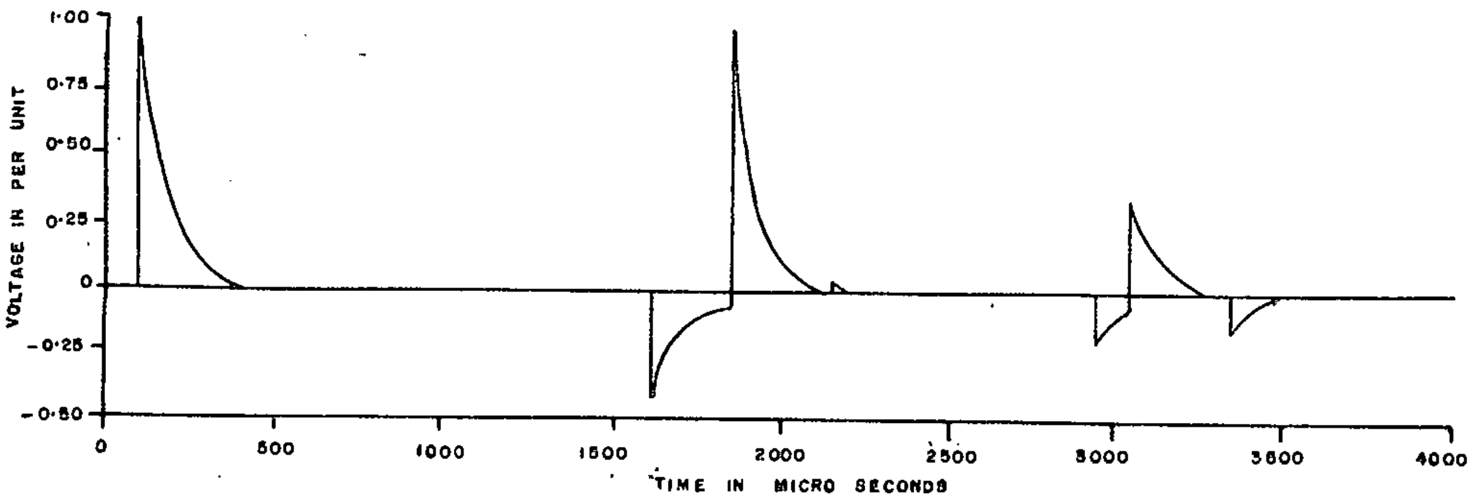
Fig. 4.3 Surge voltage wave at node 2 (Fenchuganj) for lightning stroke at node 1(Sylhet) under load at node 6(Ghorasal) considering different condition.



(a) considering only 1 reflection.

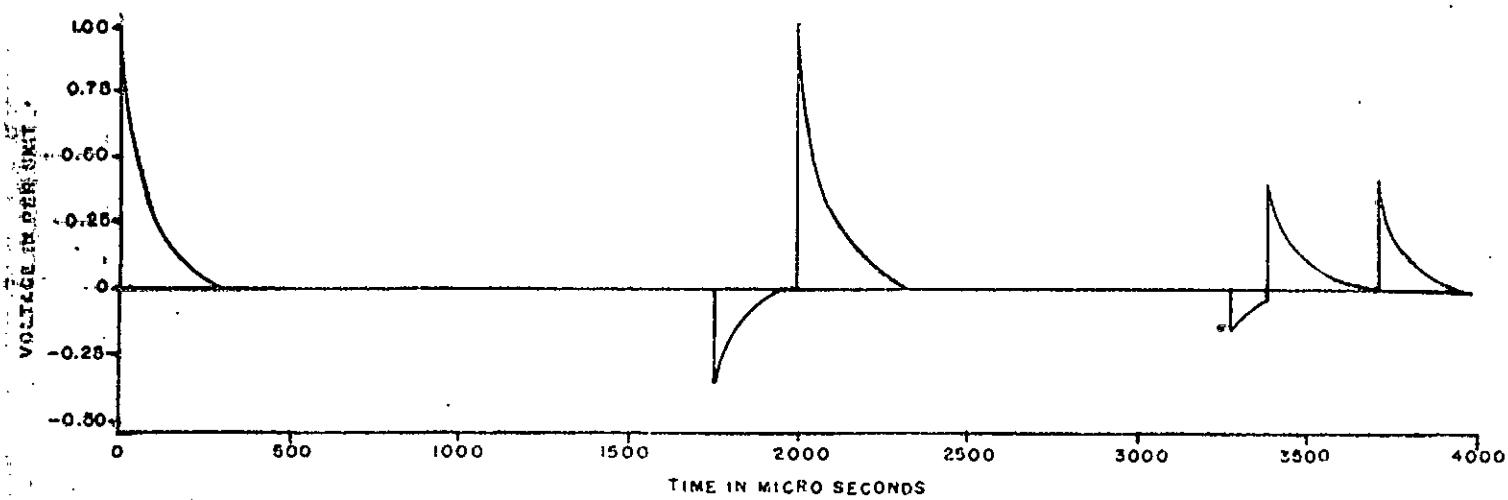


(b) considering repeated stroke of 500 μ secs.interval.

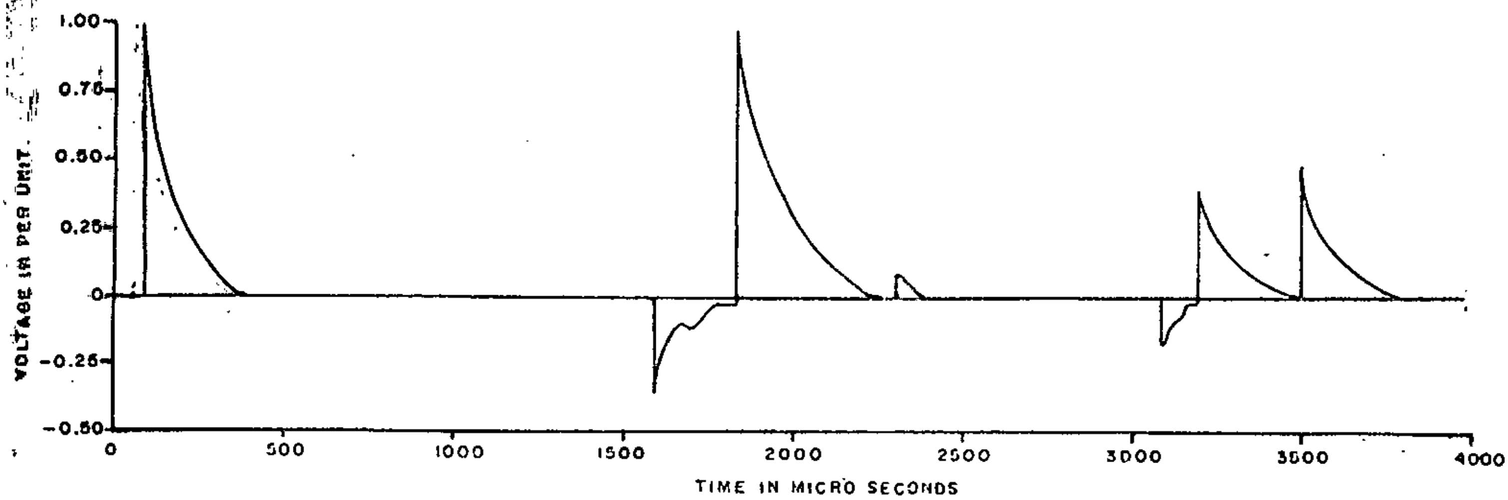


(c) considering 4 successive reflections.

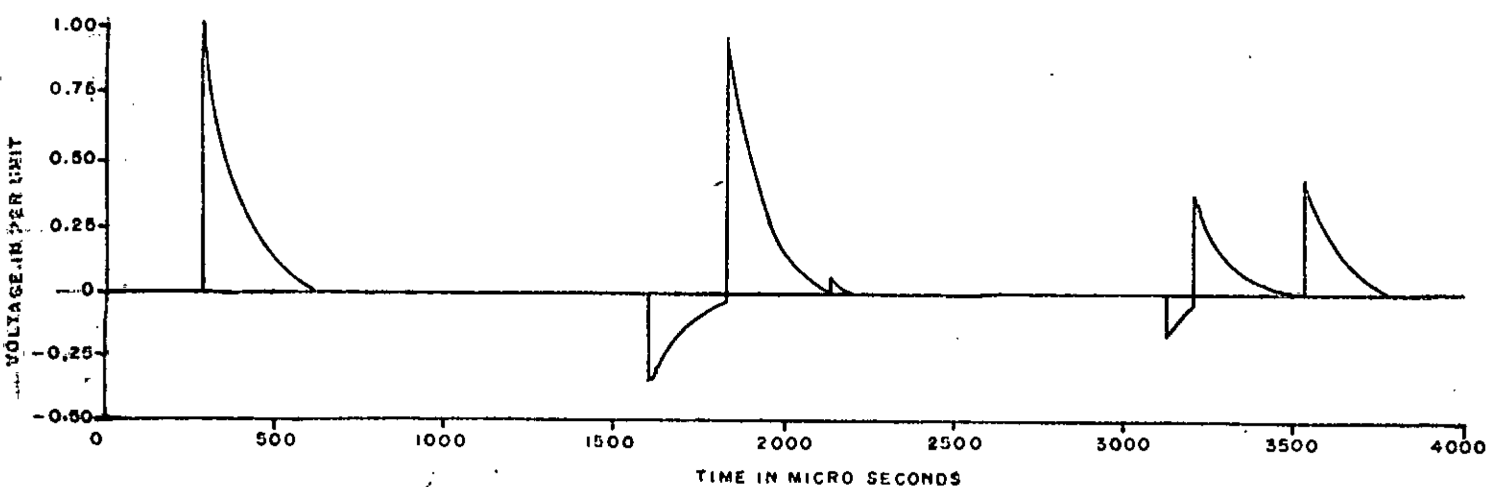
Fig. 4.4 Surge voltage wave at node 2 (Fenchuganj) for lightning stroke at node 1(Sylhet) under load at node 12(Kaptai) considering different condition.



(a) Surge voltage wave at node 1(Sylhet).

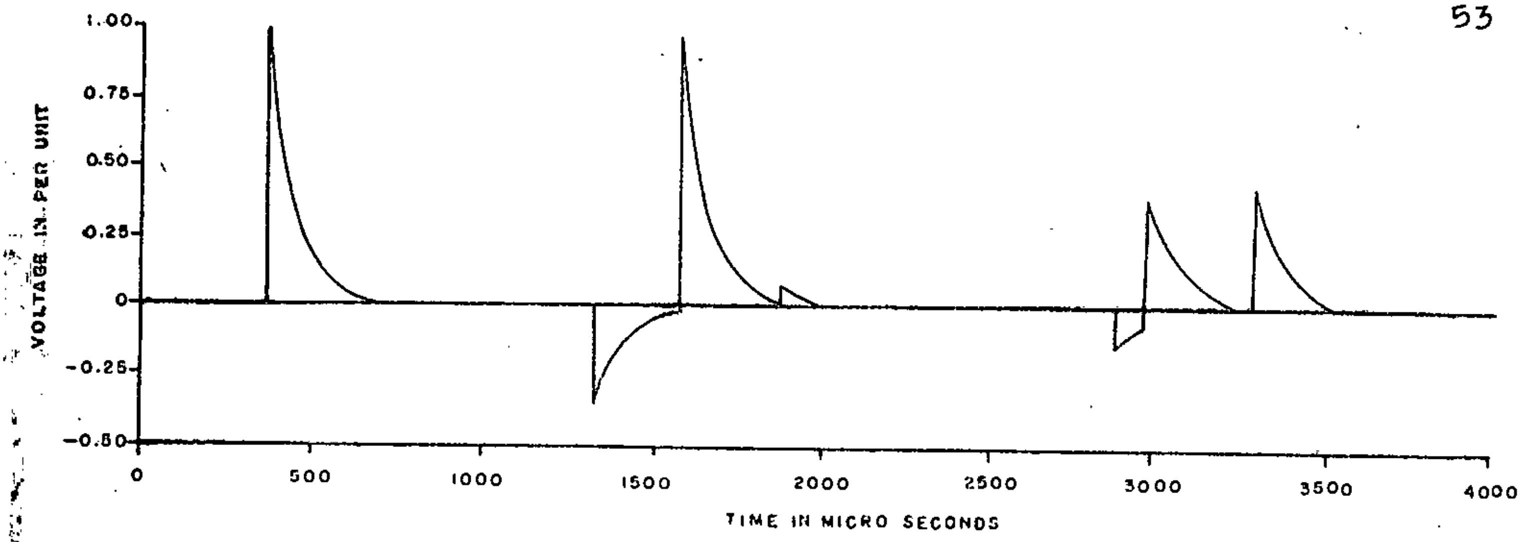


(b) Surge voltage wave at node 2(Fenchuganj).

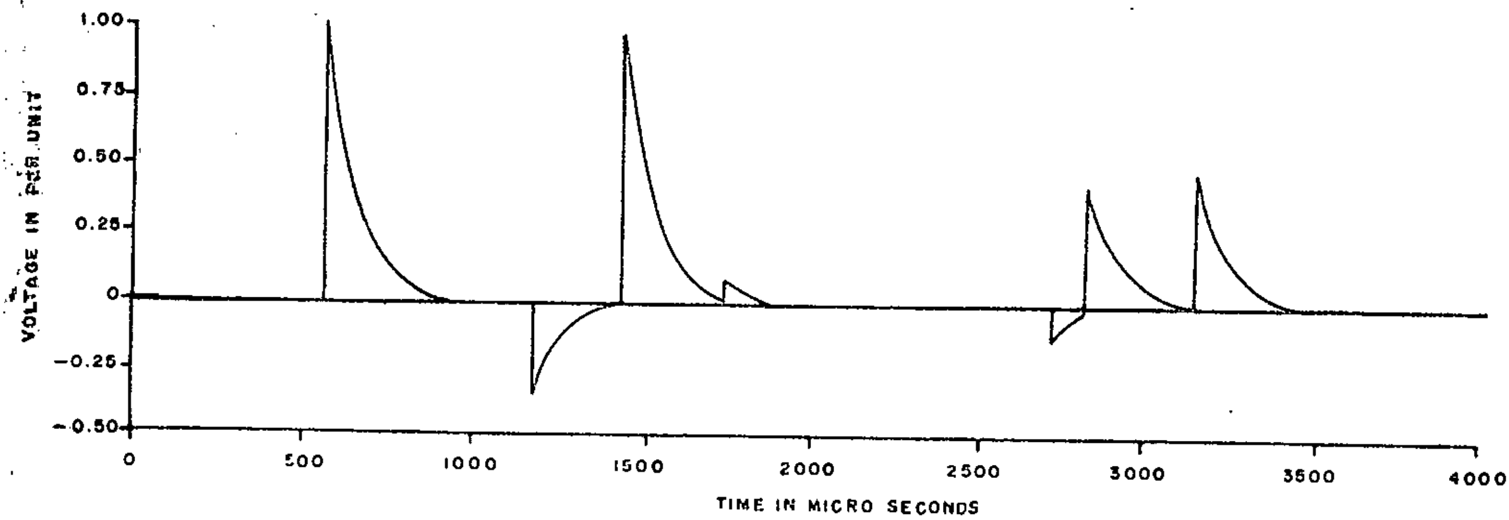


(c) Surge voltage wave at node 3(Srimangal).

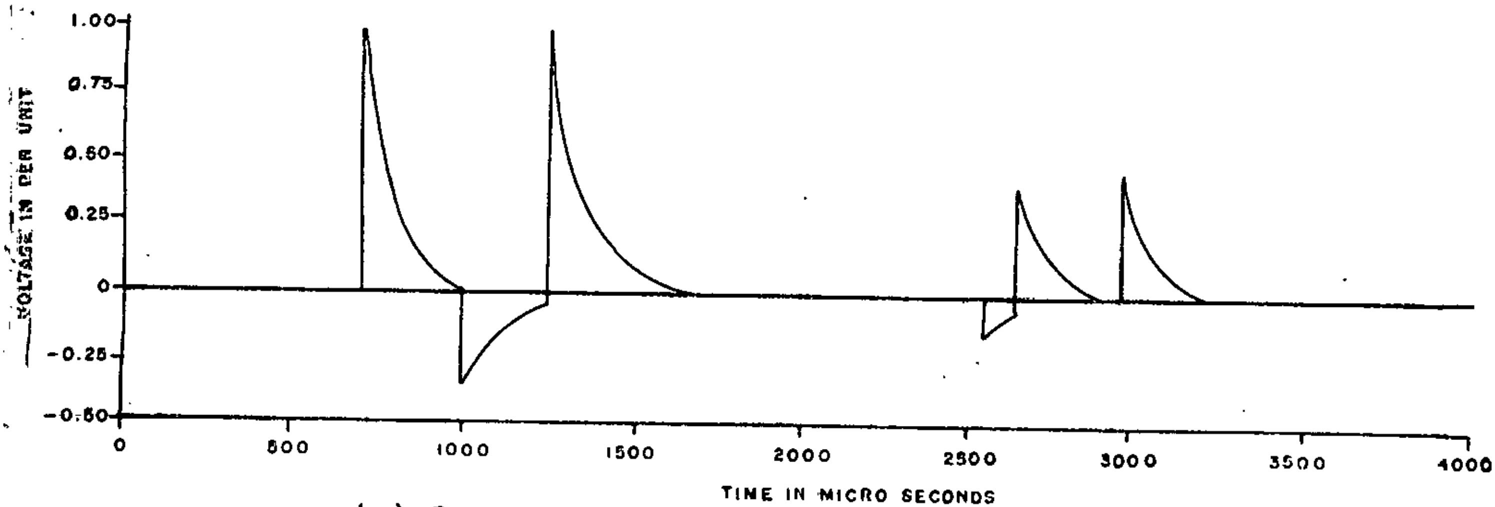
Fig. 4.5 Surge voltage wave at different nodes for single lightning stroke at node 1(Sylhet).



(a) Surge voltage wave at node 4(Shajibazar).

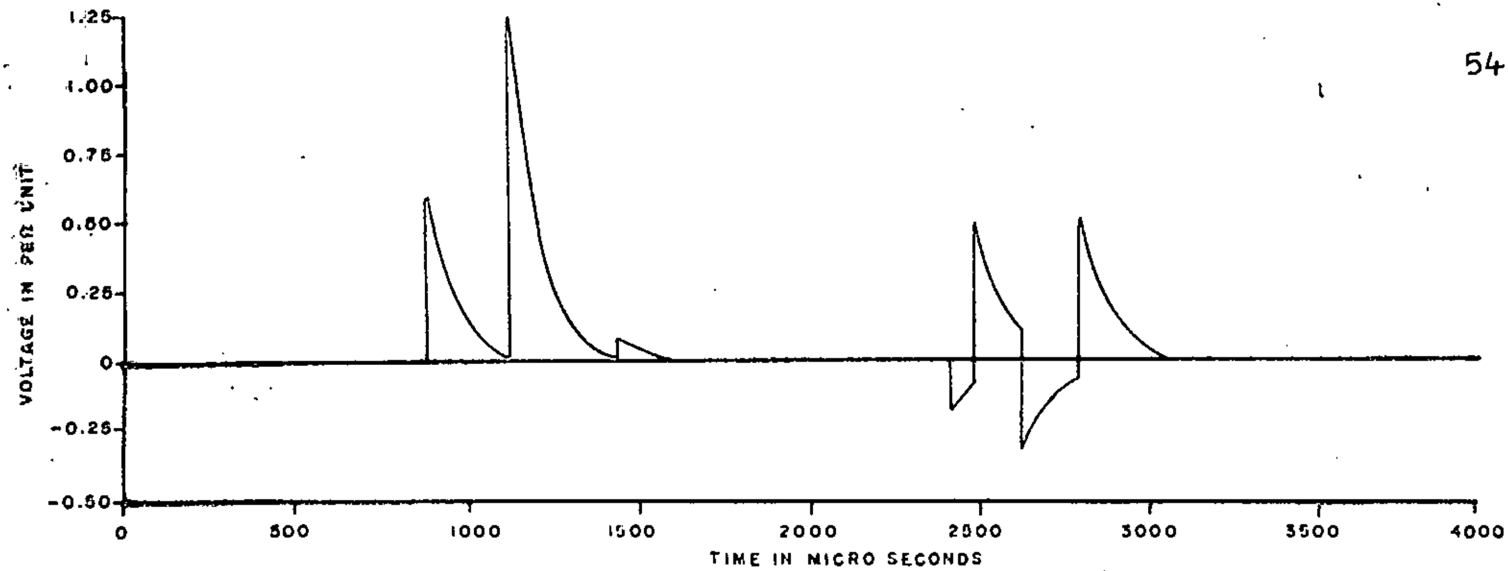


(b) Surge voltage wave at node 5(Ashuganj).

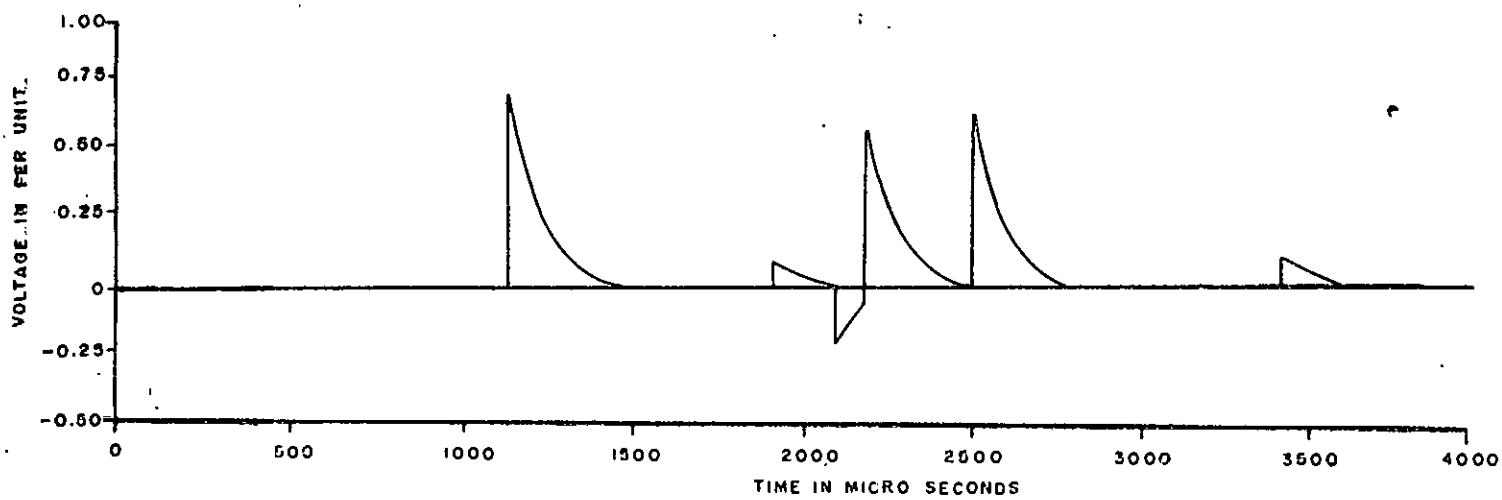


(c) Surge voltage wave at node 6(Ghorasal).

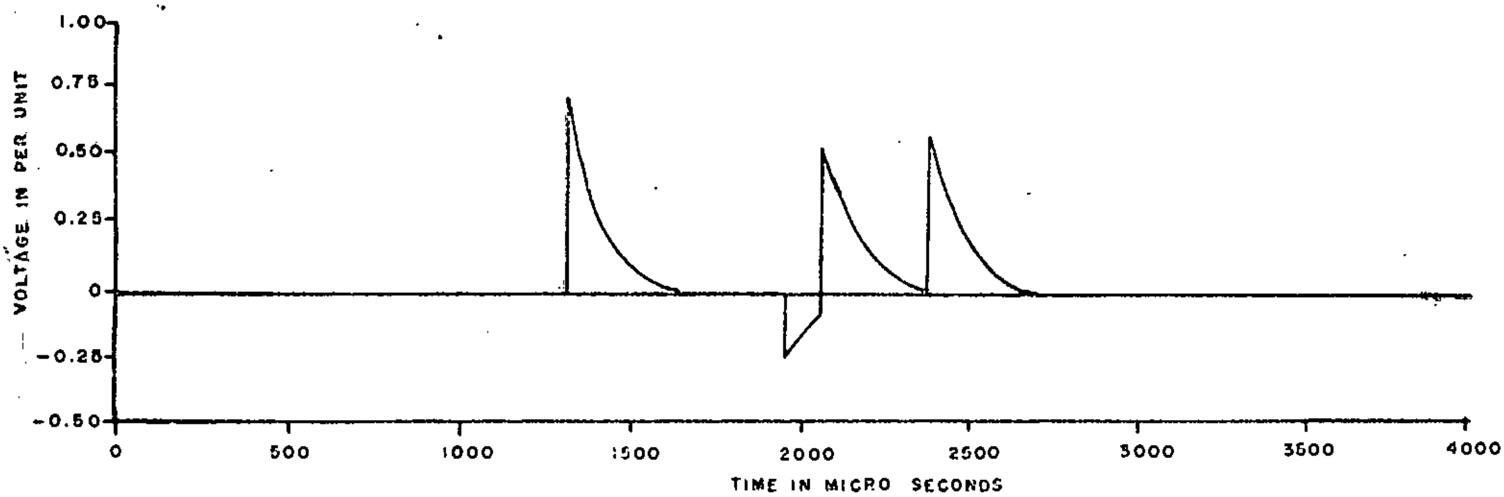
Fig. 4.6 Surge voltage wave at different nodes for single lightning stroke at node 1(Sylhet).



(a) Surge voltage wave at node 7(Siddhirganj).

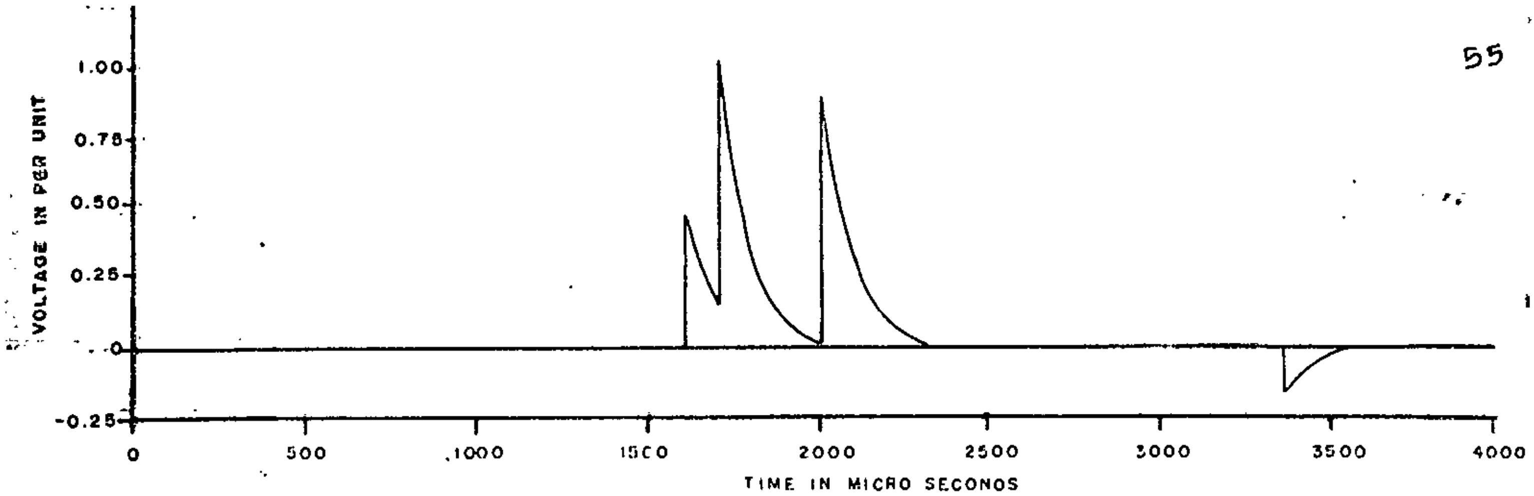


(b) Surge voltage wave at node 8(Comilla).

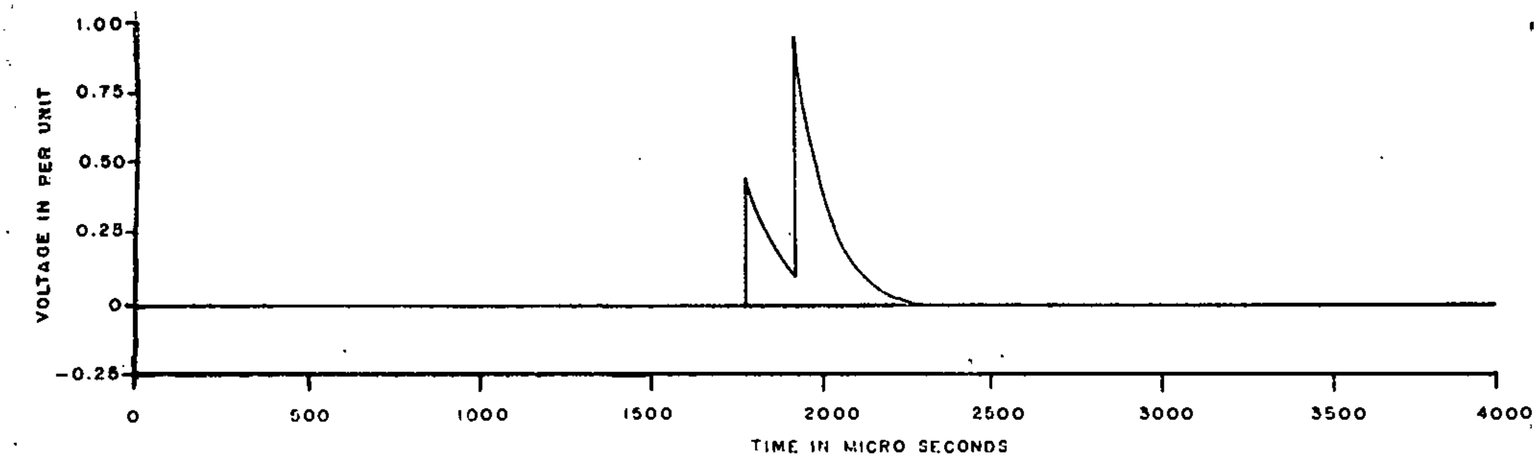


(c) Surge voltage wave at node 9(Feni).

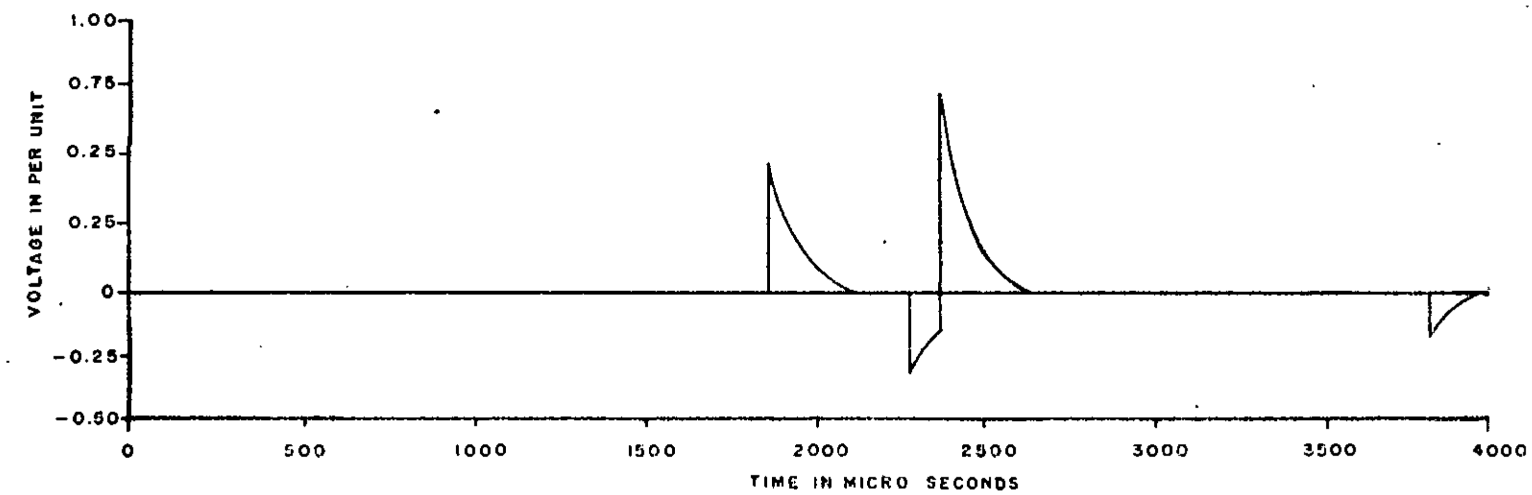
Fig. 4.7 Surge voltage wave at different nodes for single lightning stroke at node 1(Sylhet).



(a) Surge voltage wave at node 10(Madanhat).

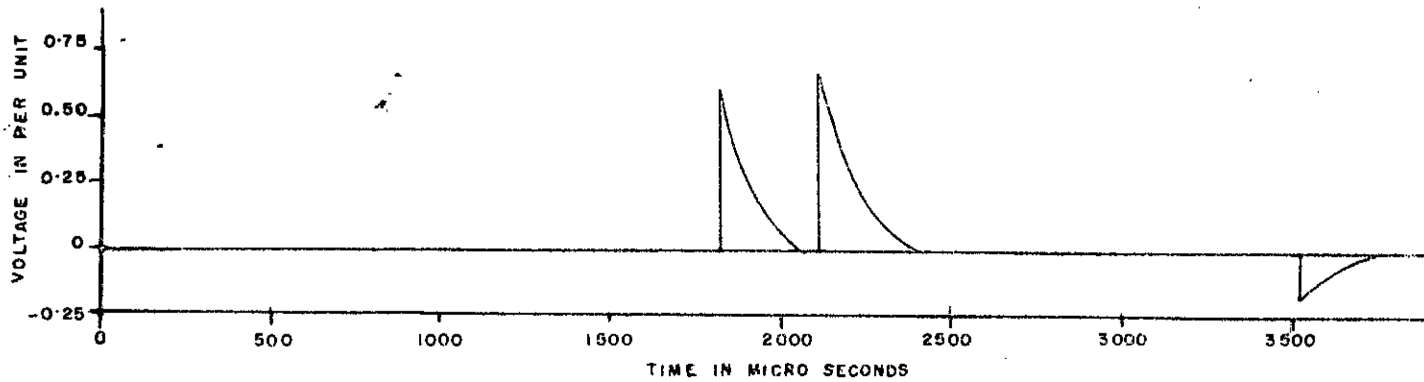


(b) Surge voltage wave at node 11(Chandraghona).

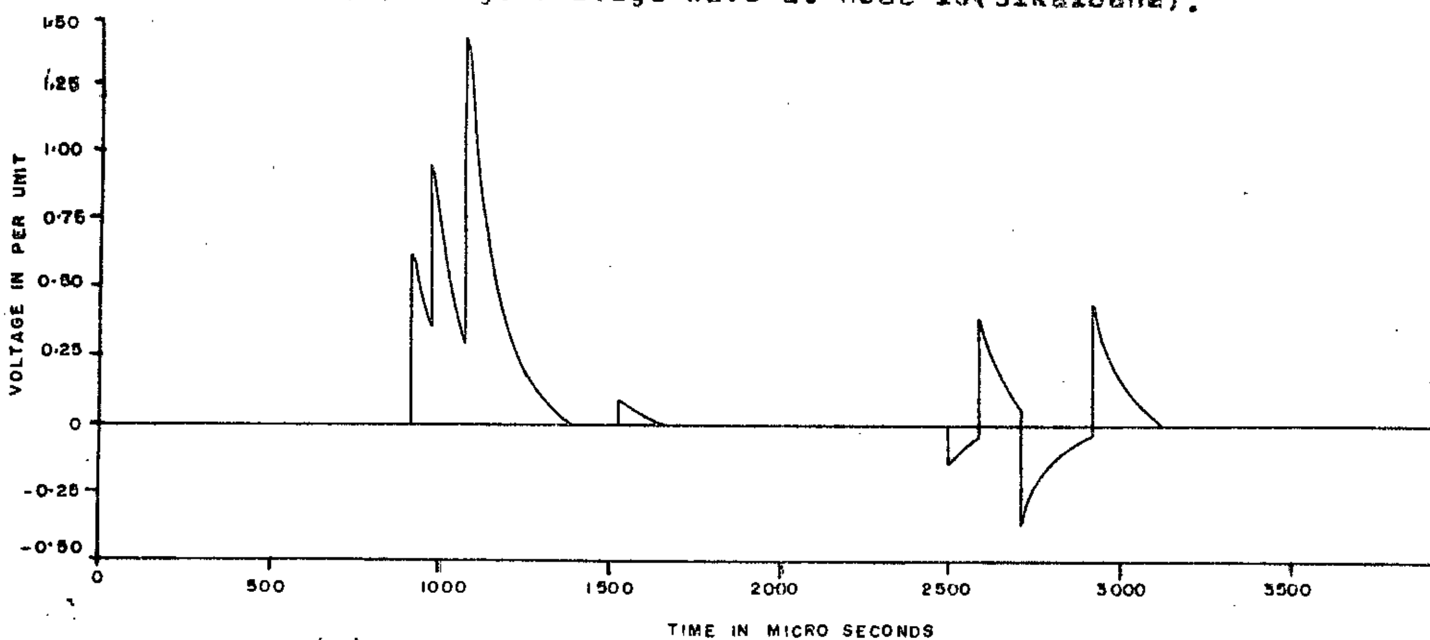


(c) Surge voltage wave at node 12(Kaptai).

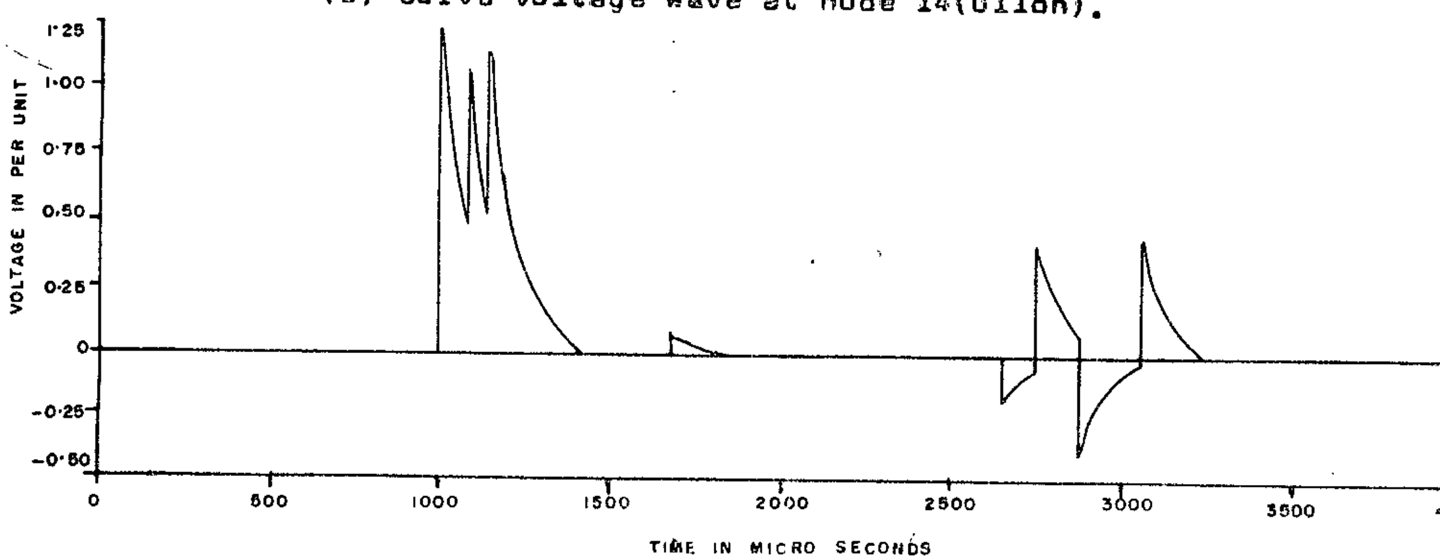
Fig. 4.8 Surge voltage wave at different nodes for single lightning stroke at node 1(Sylhet).



(a) Surge voltage wave at node 13(Sikalbaha).

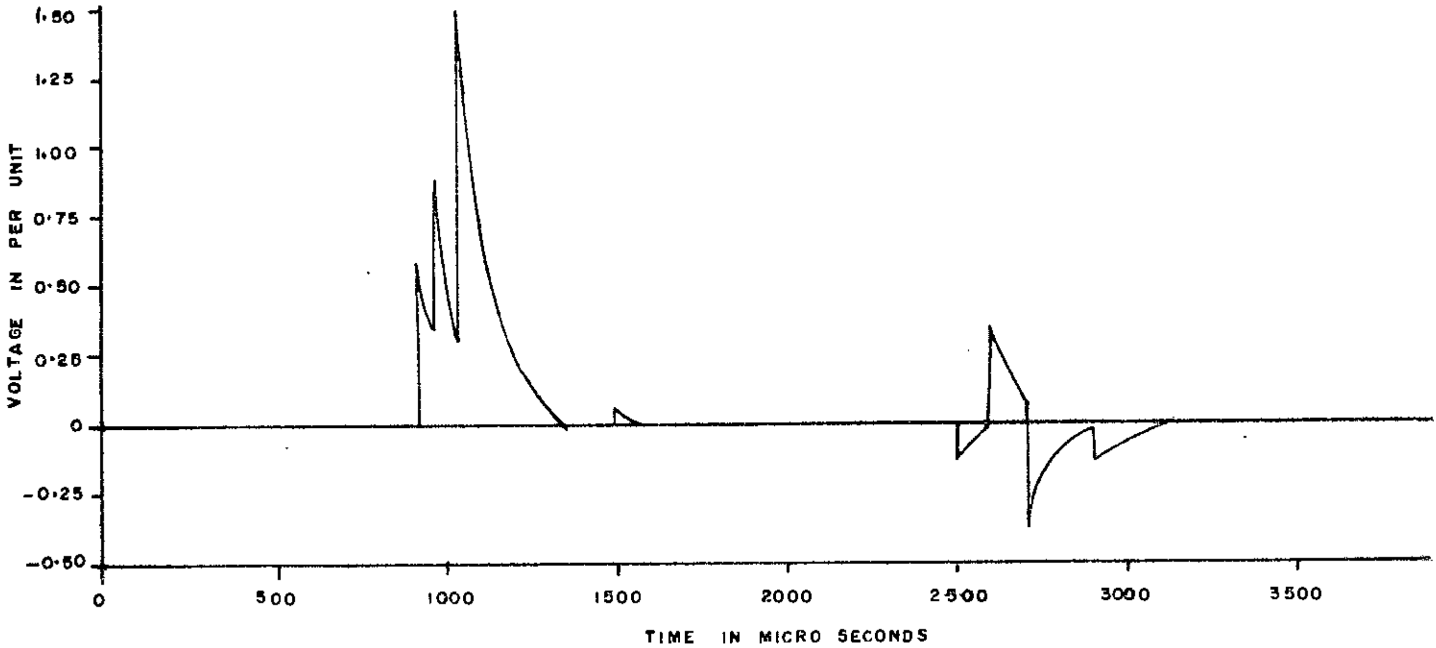


(b) Surve voltage wave at node 14(Ullon).

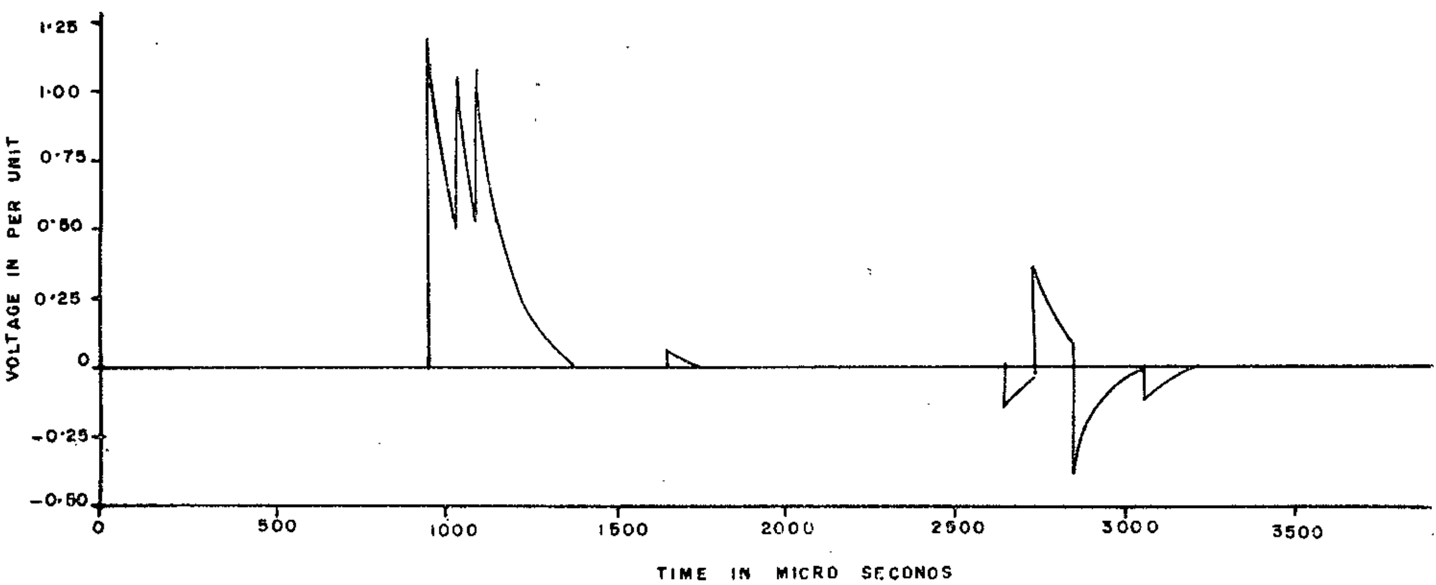


(c) Surge voltage wave at node 15(Tongi).

Fig. 4.9 Surge voltage wave at different nodes for single lightning stroke at node 1(Sylhet).



(a) Surge voltage wave at node 14(Ullon).



(b) Surge voltage wave at node 15(Tongi).

Fig. 4.10 Surge voltage wave at node 14(Ullon) and node 15(Tongi) for single lightning stroke at node 1(Sylhet) under load at node 12 (Kaptai) condition.

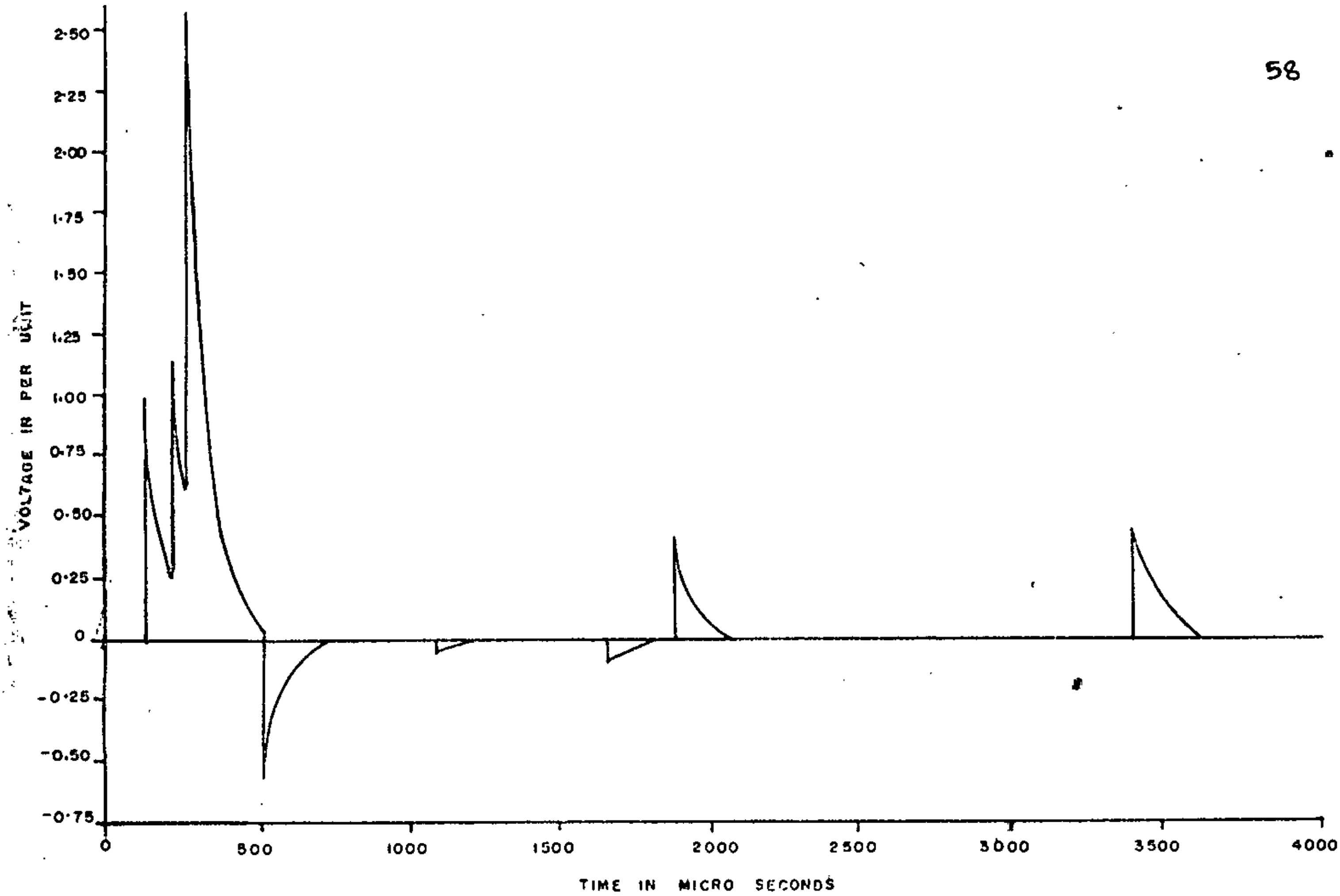


Fig. 4.11 Surge voltage wave atnode 10(Madanhat) for single lightning stroke at node 11(Chandraghona) under no load condition.

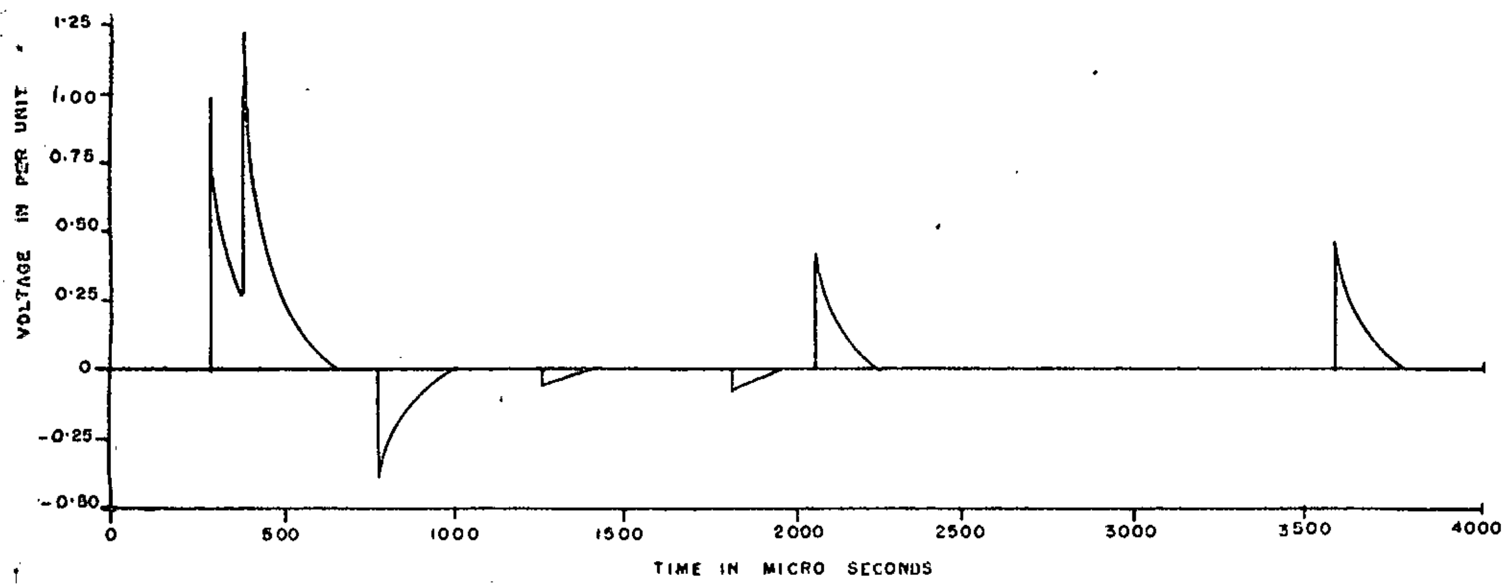


Fig. 4.12 Surge voltage wave at node 13(Sikalbaha) for single lightning stroke at node 12(Kaptai) under no load condition.

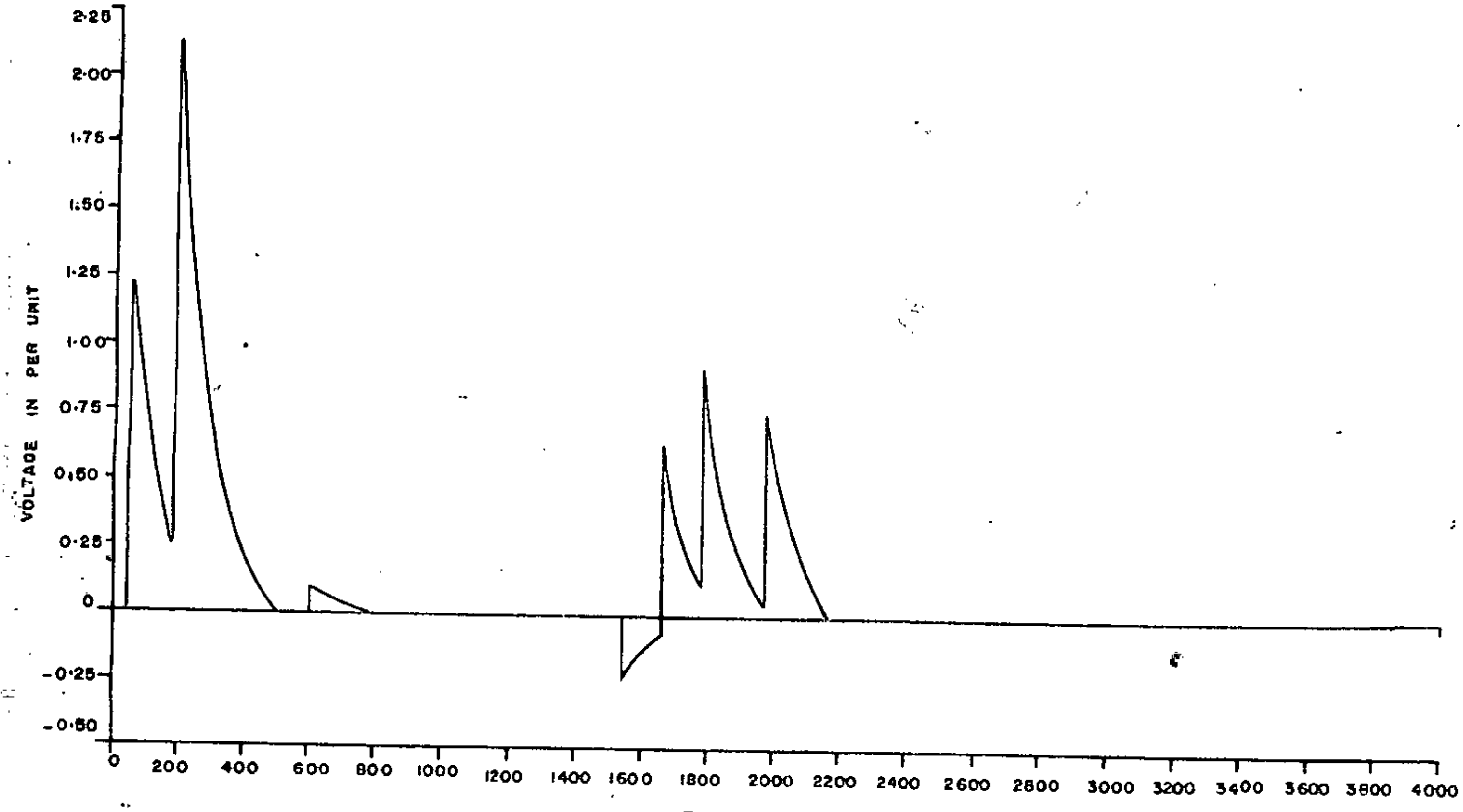


Fig. 4.13 Surge voltage wave at node 14(Ullon) for single lightning stroke at node 7(Siddhirganj) under no load condition.

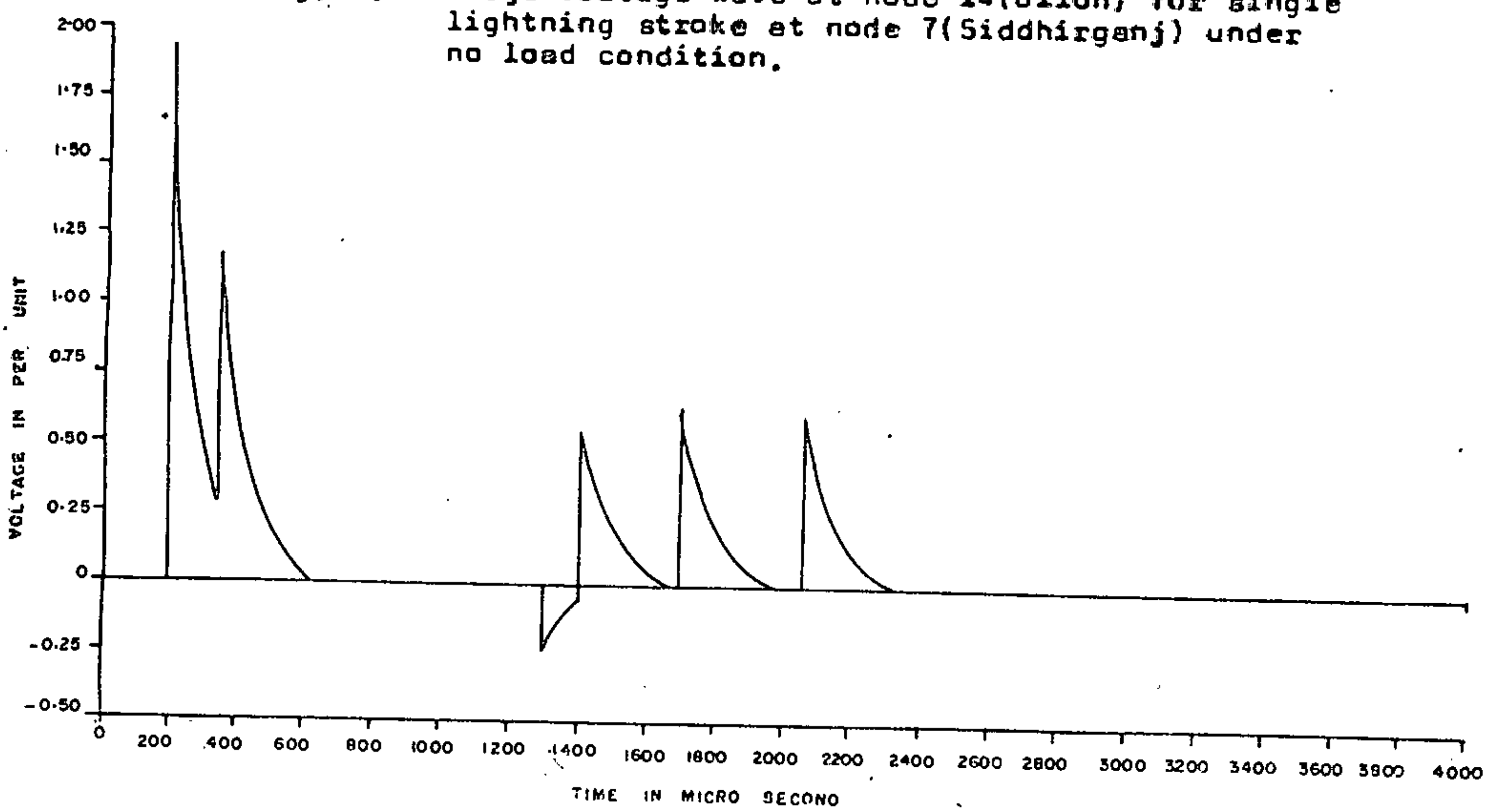


Fig. 4.14 Surge voltage wave at node 14(Ullon) for single lightning stroke at node 8(Comilla) under no load condition.

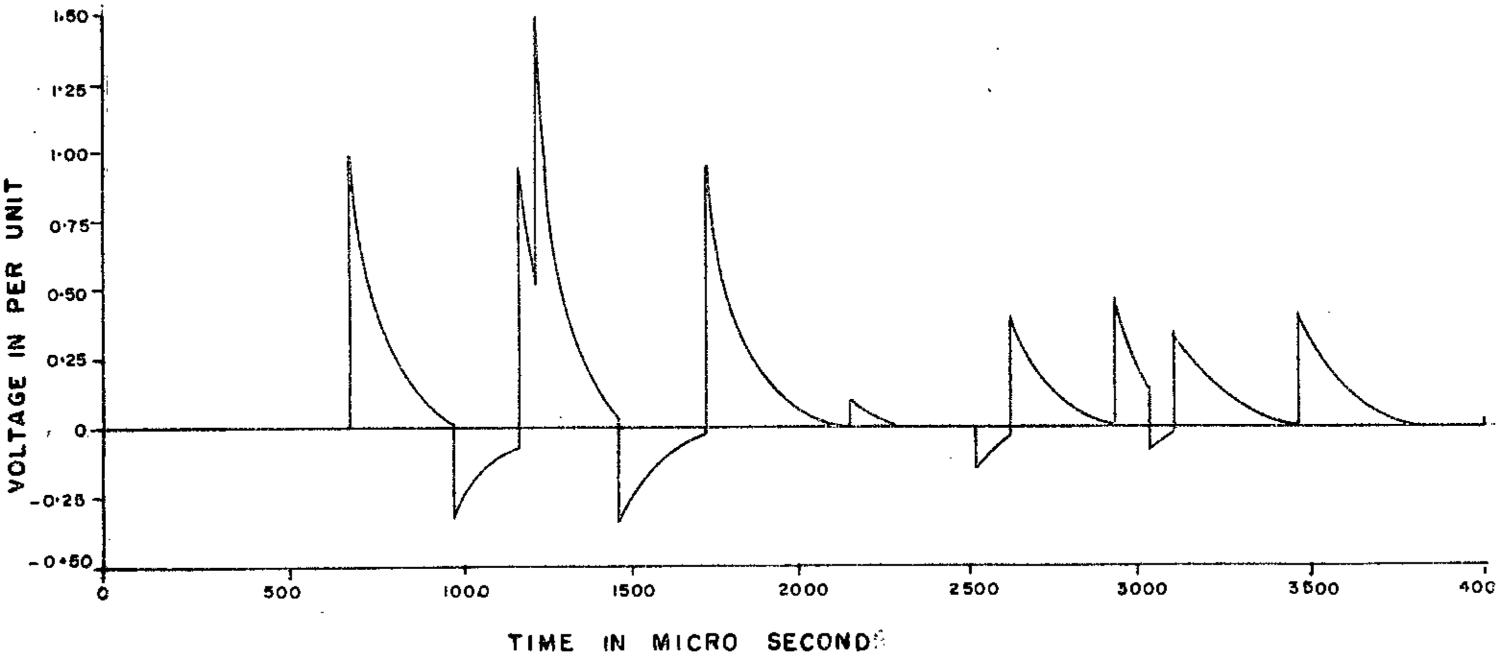


Fig. 4.15 Surge voltage wave at node 6(Ghorasal) for repeated lightning stroke of 500 micro seconds interval at node 1(Sylhet) under no load condition.

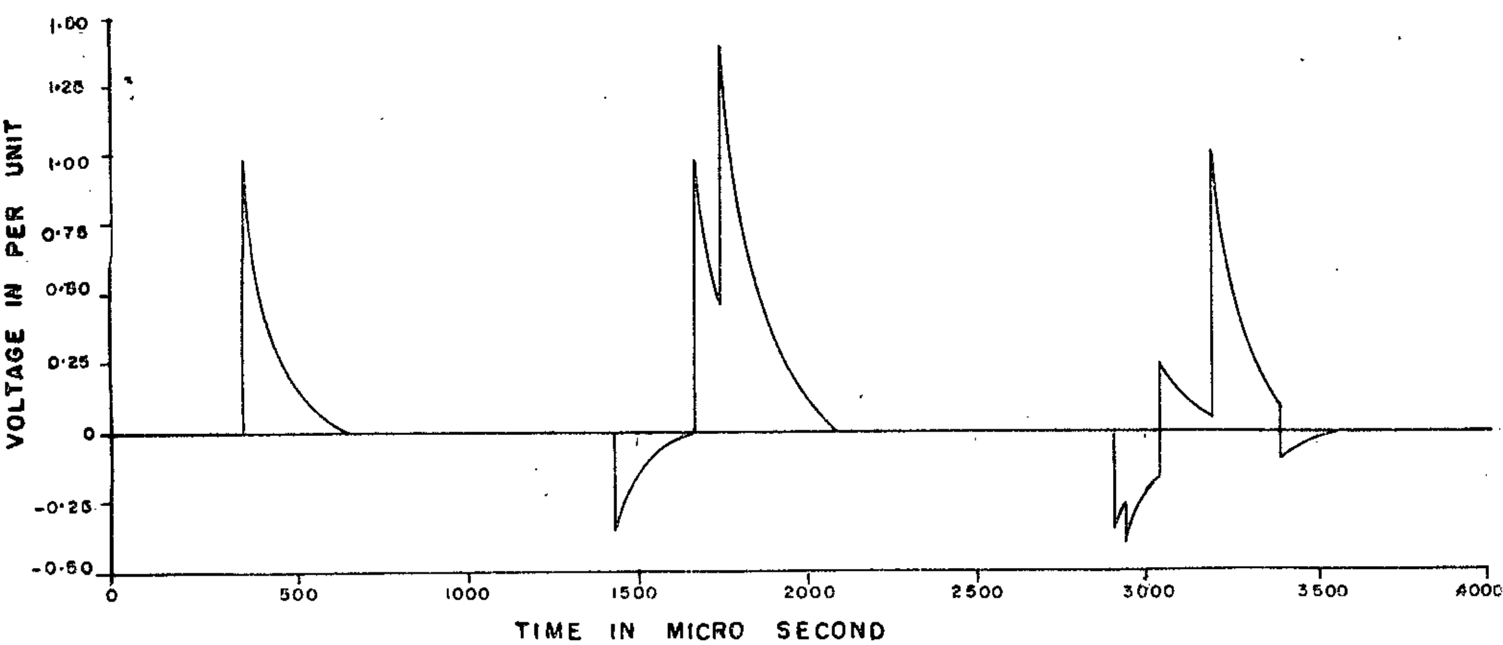


Fig. 4.16 Surge voltage wave at node 3(Srimangal) for repeated stroke of 1500 micro seconds interval at node 1(Sylhet) under load at node 12 (Kaptai) condition.

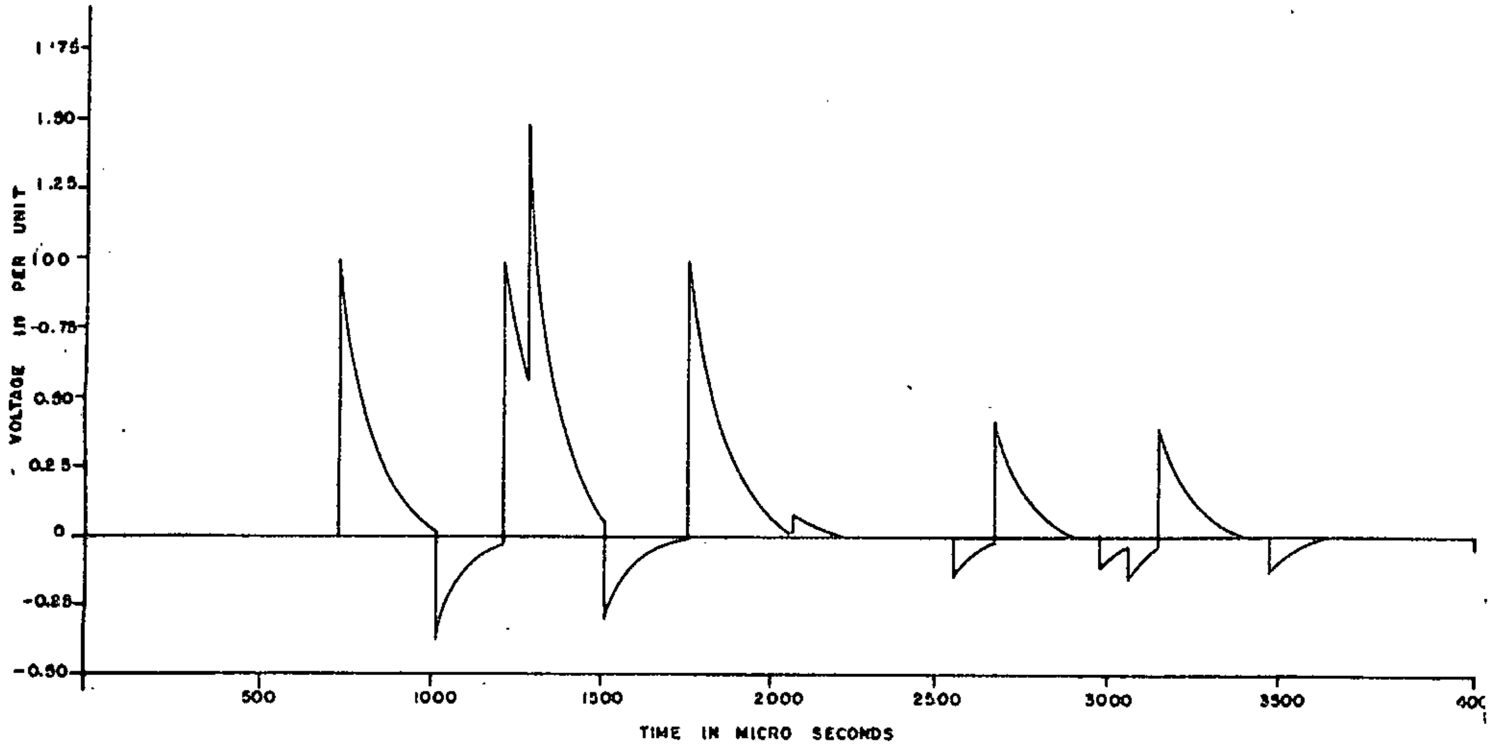


Fig. 4.17 Surge voltage wave at node 6(Ghorasal) for repeated lightning stroke of 500 micro seconds interval at node 1(Sylhet) under load at node 12(Kaptai) condition.

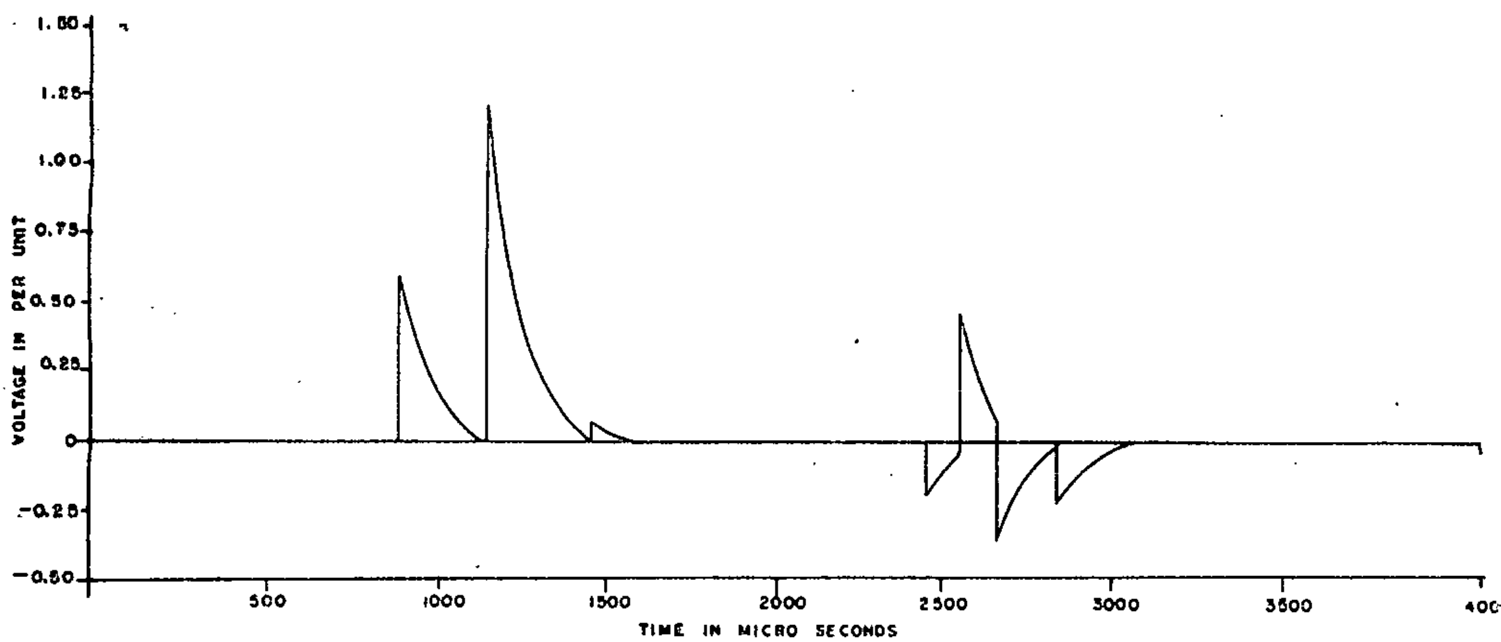
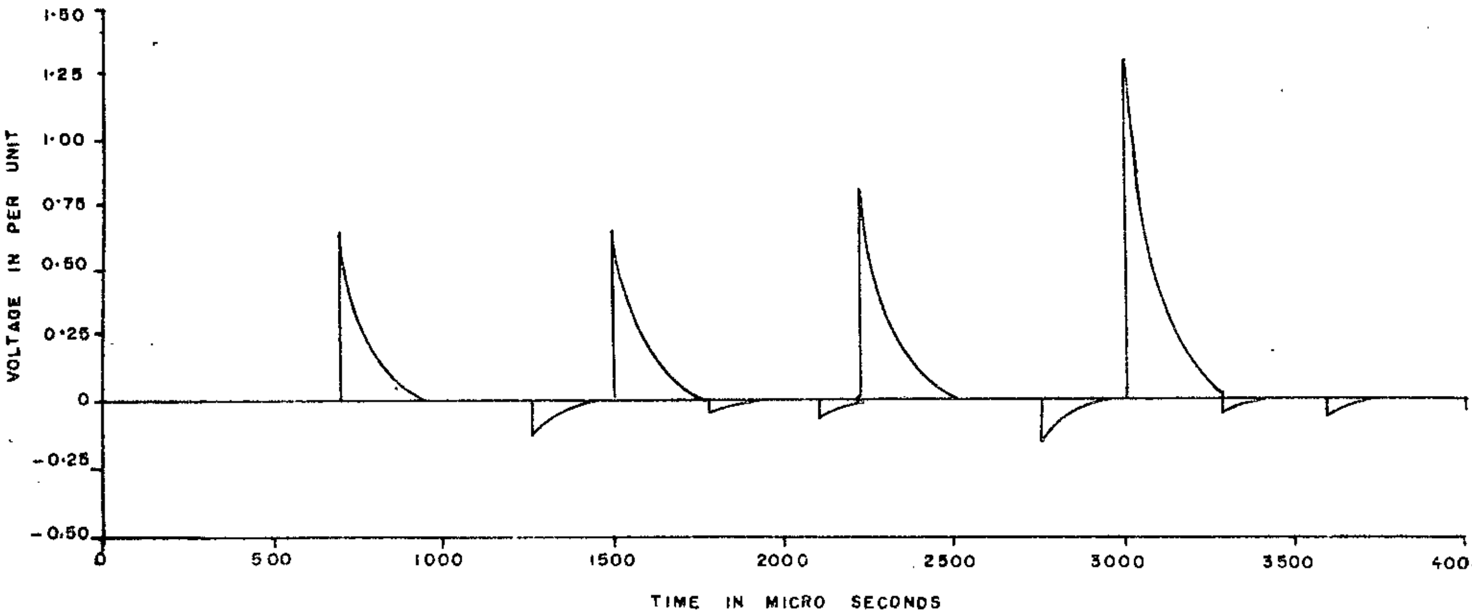
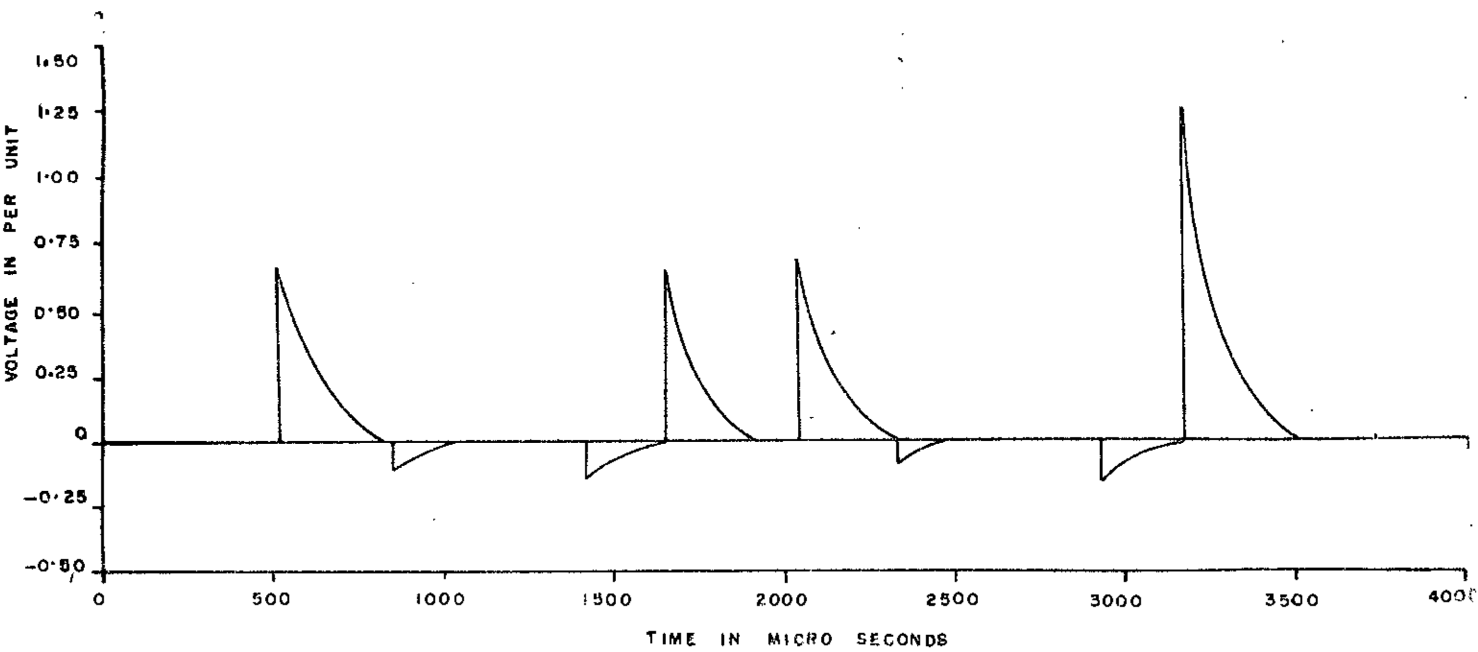


Fig. 4.18 Surge voltage wave at node 7(Siddhirganj) for single lightning stroke [ ] at node 1(Sylhet) under load at node 12(Kaptai) condition.

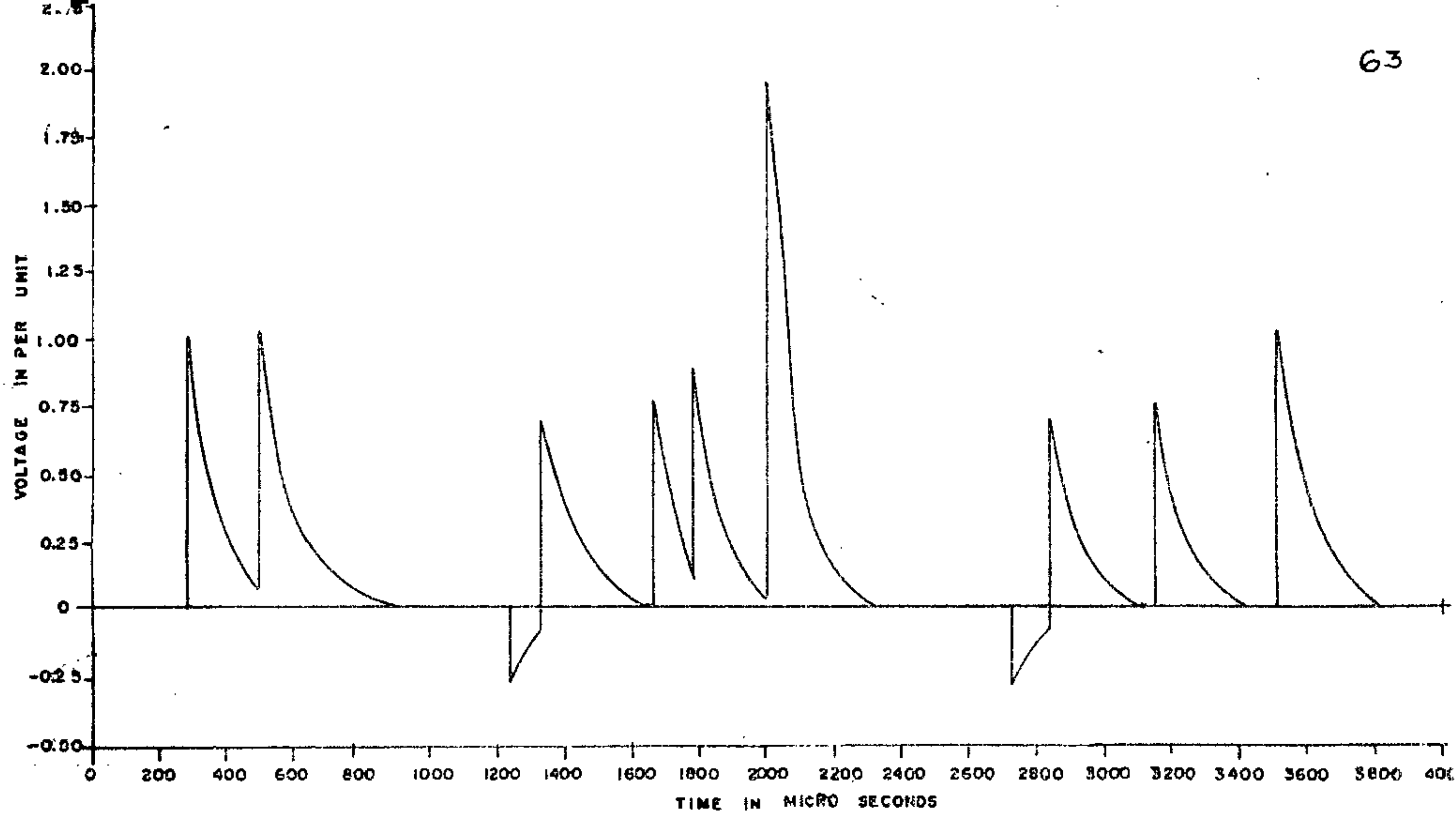


(a) Surge voltage wave at node 8(Comilla).

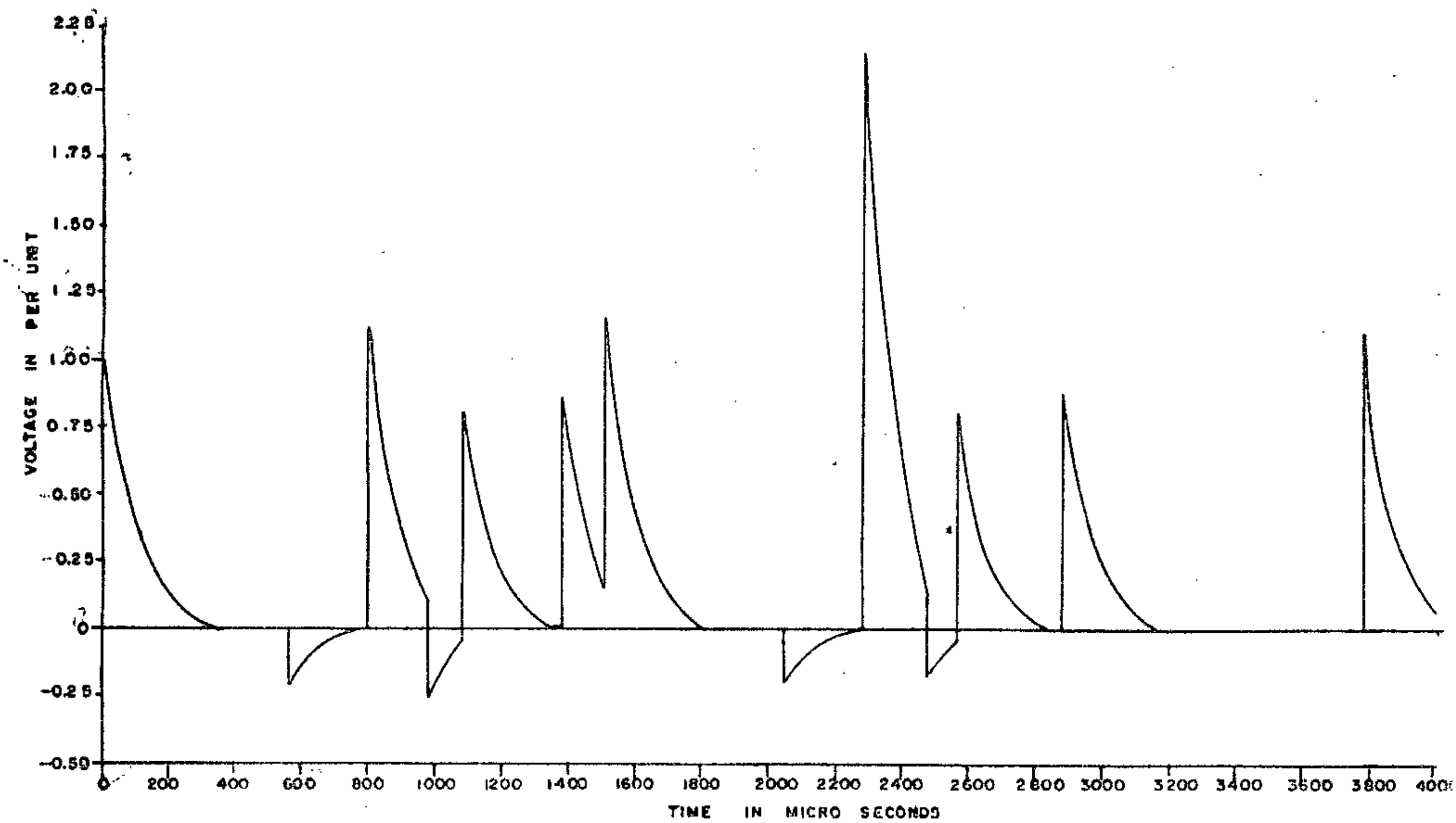


(b) Surge voltage wave at node 9(Feni).

Fig. 4.19 Surge voltage wave at node 8(Comilla) and node 9(Feni) for repeated stroke of 1500 micro seconds interval at node 12(Kaptai) under no load condition.



(a) Surge voltage wave at node 7(Siddhirganj).



(b) Surge voltage wave at node 8(Comilla).

Fig. 4.20 Surge voltage wave at node 7(Siddhirganj) and node 8(Comilla) for repeated lightning stroke of 1500 micro seconds interval at node 8(Comilla) under no load condition.

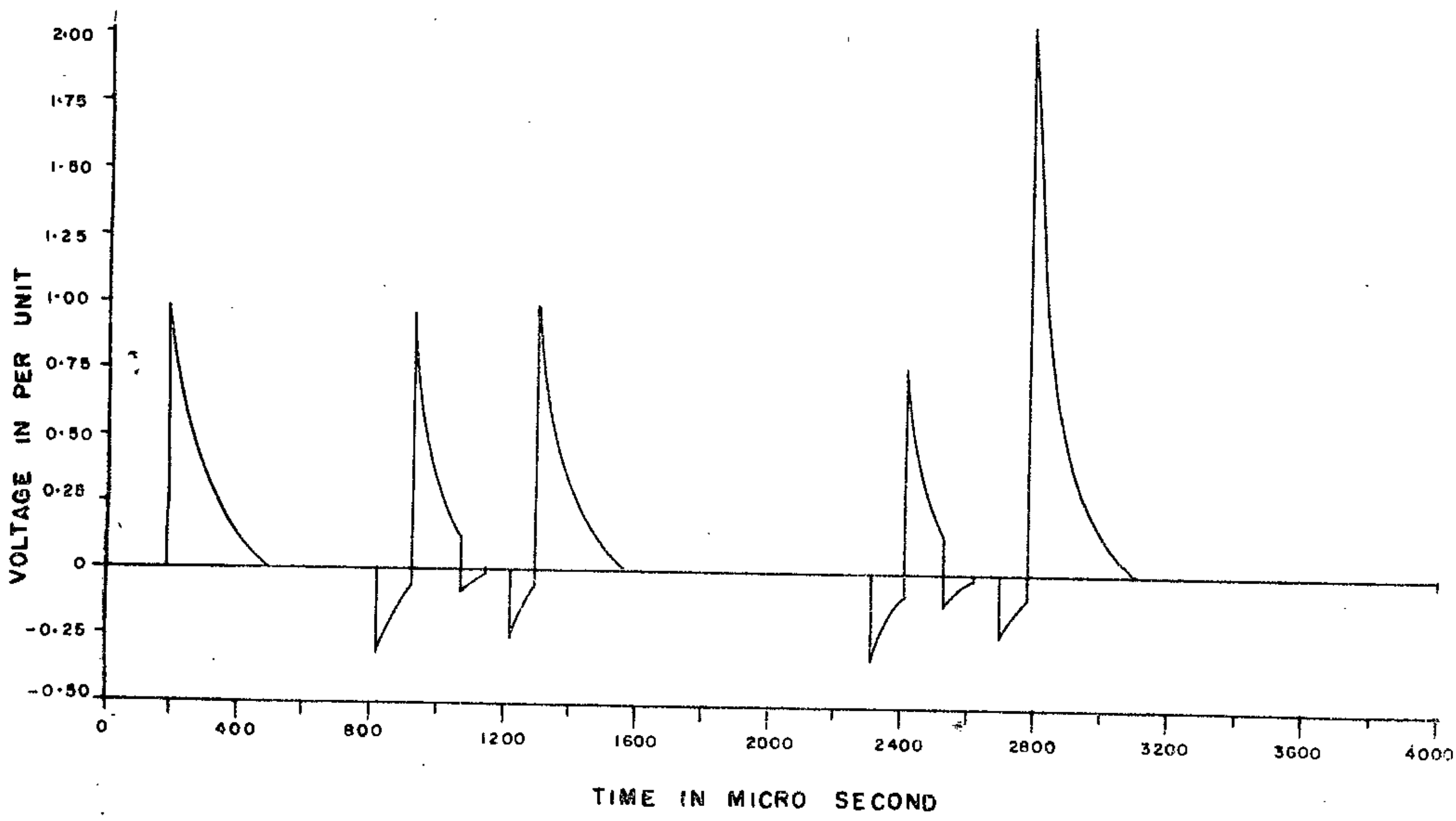


Fig. 4.21 Surge voltage wave at node 9(Feni) for repeated lightning stroke of 1500 micro seconds interval at node 8(Comilla) under load at node 12(Kaptai) condition.

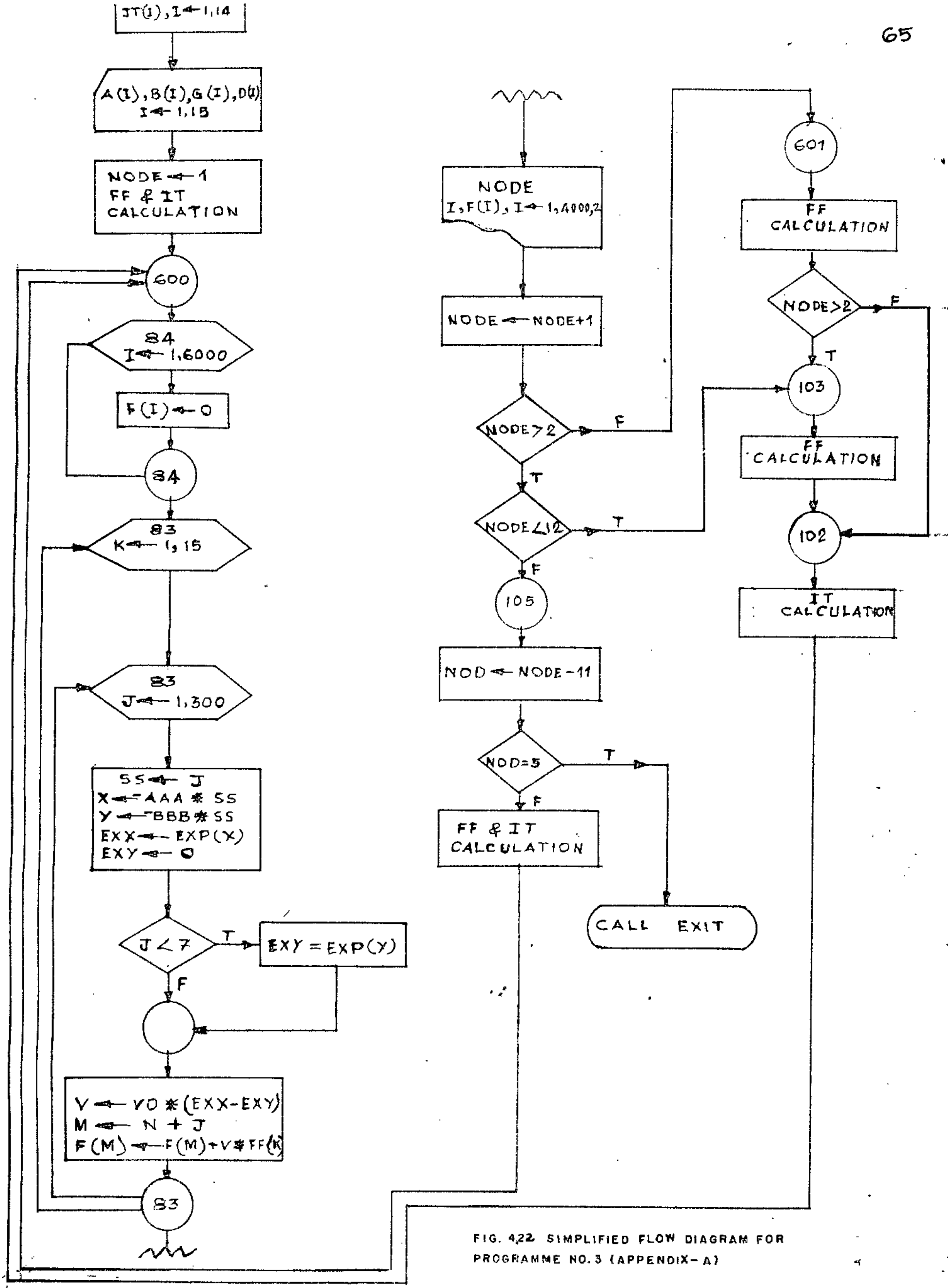


FIG. 4.22 SIMPLIFIED FLOW DIAGRAM FOR PROGRAMME NO. 3 (APPENDIX-A)

CHAPTER - 5

ANALYSIS OF RESULTS

Analysis of computer results are shown in this chapter. For lightning stroke at different nodes the effect at other nodes are explained systematically. In analysing the results computer print outs and check programmes are mostly consulted.

5.1 Analysis of Surge Voltage Wave at Node 2 (Fenchuganj)

Fig. 4.2 through 4.4 show the surge voltage wave pattern at node 2 (Fenchuganj) for lightning stroke at node 1(Sylhet). The lightning surge appears undiminished (for no load condition) at 106 microseconds after the stroke at Sylhet, as this time is required for the wave to travel the distance. The second positive peak appears at 1873 micro-seconds after the stroke at Sylhet with a magnitude of 0.98 p.u. This is the wave which is reflected from node 15 (Tongi), which is open circuited. The other positive and negative peaks are of lower magnitude. In Fig. 4.2(b) the effect of two lightning stokes of 500 micro-seconds interval is shown. The result is almost liner addition of Fig. 4.2(a) waves. There is no danger of build up as the successive strokes do not superimpose one another. In Fig.4.2(c) the effect of considering four successive reflections from adjacent two nodes is shown. In all other studies only one reflection from each node is considered. In this study for each wave 4 successive reflections from adjacent two nodes are considered to observe whether any difference between considering only 1 reflection and 4 reflections appears. It is observed that there is actually no difference between Fig. 4.2(a) and 4.2(c). This is because successive reflections diminish the magnitude of the wave. As reflection and transmission coefficients for forward and backward moving waves are less than one, their multiplication successively diminish, so the total effect is same as for one reflection.

The effect of connecting a load of 100 ohm at node 6(Ghorashal) is shown in Fig. 4.3(a), (b) and (c). The first peak remains unchanged but the second peak becomes negative at 1327 micro-seconds after the stroke. The full lightning surge was passing through node 6 when there was no load connected, as impedance of Asbuganj-Ghorasal (Z_5) section and Ghorasal - Siddhirganj (Z_6) section were same. With load connected at Ghorasal some portion of the indicent wave is reflected and due to value of coefficients it is negative. The effect of repeated stroke is like that of no load condition. There is also no appreciable change when 4 successive reflections are considered.

The effect of connecting a load of 80 ohm at node 12(Kaptai-gona) is shown in Fig. 4.4(a), (b) and (c). The effect is approximately same as no load condition. This can be explained as - the wave returning from far end reduces to zero before it reaches Fenchuganj, so there is no appreciable change when we considered a load at far and Kaptai. The wave shape is same as no load condition.

5.2 Analysis of Surge Voltage Waves at all Nodes for Single Stroke at Node 1(Sylhet) under no load Condition.

The surge voltage waves at all nodes for single stroke at node 1(Sylhet) under no load condition are shown in Fig.4.5 through 4.9. At node 1(Sylhet) the first peak is the replica of lightning stroke and appears at zero time. Second positive peak is the wave reflected from open end node 15 (Tongi). The magnitude is 0.97 p.u. and it appears at 1980 micro seconds after the stroke. This wave has passed many transmission and reflection on its way, but then also its magnitude is 0.97 p.u., this is because the voltage doubles at open end node Tongi. The first negative peak of 0.36 p.u. magnitude is the reflected wave from node 7(Siddhirganj). The other reflected waves are reflections from end nodes, i.e. nodes 10(Madanhat), 13(Sikalbaha), 12(Kaptai) respectively. The voltage wave at node 2(Fenchuganj) and node 3(Srimangal) are almost identical but shifted in time. This is because distance between them is 30.47 miles and travel time is 164 micro seconds.

The surge voltage wave pattern at node 4(Shajibazar) and node 5(Ashuganj) is identical and only a bit time shifted. The first positive peak appears at 393 microseconds after the stroke and the second positive peak at 1589 microseconds and it is the reflected wave from node 15 (Tongi). The last two positive peak are from far end nodes. The wave at node 5(Ashuganj) is identical as Shejibazar. The wave pattern at node 6(Ghorasal) is a bit different as two peaks are closed together. The first peak appears at 718 microseconds. The negative peak appears at 1024 microseconds and is the reflected component from node 7(Siddhirganj). The next positive peak appears at 1264 microseconds before reflected negative component diminishes. The second positive peak is the reflected component from open end node 15(Tongi). The next smaller reflections are from far end nodes.

Interesting phenomena occurs at node 7(Siddhirganj). The stroke at Sylhet reappears at Siddhirganj at 871 microseconds after the stroke and the magnitude is 0.62 p.u. The next peak has a magnitude of 1.27 p.u. This is the component reflected from open end node 15(Tongi). At open end node Tongi the wave returns with double magnitude according to the well-known doubling(8) up of a voltage wave as it strikes the end of an open-circuited line. The other waves are reflected component from far end nodes. The surge wave at node 8(Comilla) and node 9(Feni) are not so much significant.

At Madanhat the first peak appears at 1634 microseconds and has a value of 0.46 p.u. Before this wave vanishes another wave reflected from open end node 13(Sikalbaha) with a magnitude of 0.93 p.u. returns then the resultant magnitude becomes 1.05 p.u. at 1726 microseconds. The third peak has a magnitude of 0.92 p.u. At node 11 (Chandraghona) the peaks have magnitdde of 0.46 p.u. and 0.98 p.u. No other reflection appears within 4000 micro seconds. The highest peak at node 12(Kaptai) is 0.74 p.u. at 2323 microseconds. The peak is low as negative component is present at that instant.

There is no noticeable peak at node 13(Sikalbaha). Most significant node is node 14(Ullon) and node 15(Tongi). At node 14(Ullon) there is a peak of 1.46 p.u. at 1060 micro seconds after the stroke at Sylhet. This peak is the summation of reflected component from end node Tongi and node Siddhirganj. The position and distance of node Ullon is such that it is only 9.5 miles from fork node Siddhirganj and 12.8 miles from open end node Tongi. So it is most dangerous node in the system. The peak value at node 15(Tongi) is about 1.11 p.u. at 1111 micro seconds.

5.2.1 Analysis of Surge Voltage Wave at all Nodes for Single Stroke at Node 1(Sylhet) under Different Load Conditions

This study is performed for one load at a time at node 6(Ghorasal) and node 12(Kaptai). Functions and times are calculated and checked. Only those curves are drawn where voltage build up possibility was prominent.

First let load at node 6(Ghorasal) condition be discussed. When a load is connected at Ghorasal, the value of alpha, beta, gamma and delta changes. The result is change in the shape and reduction in magnitude of wave at all nodes. This is because, before any load connected at Ghorasal, this section has a matching, so full wave could pass either direction without reflection and facilitate build up. This reduces the magnitude considerably, e.g. voltage magnitude at node 14(Ullon) is 0.44 p.u. but at no load condition it was 1.46 p.u.

When a load is connected at node 12(Kaptai) there is not so much change in the wave shape at different nodes. From previous discussion in para 5.2 it is noted that reflected component from node 12(Kaptai) has little significant in the wave shape at different nodes. Due to load at Kaptai the reflected component becomes negative which earlier at no load condition was positive and is reduced by about 68%. This effect can be seen in Fig. 4.10(a) and (b). The end portion of the wave is reduced and negative which was earlier positive (Fig.4.9(b) and (c)).

5.3 Analysis of Surge Voltage Wave at all Nodes for Single Stroke at Node 12(Kaptai)under different Load Conditions

The result of this study shows that there is no appreciable chance of voltage build up at any node except at node 13(Sikalbaha). This is also true for load at node 12(Kaptai) and node 6(Ghorasal) condition. This is due to system configuration. But there are posibility of voltage piling at node 8(Comilla) and 9(Feni) for repeated stroke of 1500 micro-seconds.

The second peak in Fig. 4.12 is of magnitude 1.25 p.u. This is because reflected component from node 10(Madanhat) superimpose with incident component of node 13(Sikalbaha) for no load at nodes 12(Kaptai) and 6(Ghorasal) conditions.

5.4 Analysis of Surge Voltage Wave at Adjacent Nodes for Single Stroke at Node 11(Chandraghona), 7(Siddhirganj) and 8(Comilla)

Before writing the computer programme no.5(refer Appendix-A), simple check up calculations are made by electronic calculator to find the probable nodes for voltage build up under lightning stroke at other nodes. Nodes 11(Chandraghona), 7(Siddhirganj) and 8(Comilla) are selected for the study.

For a single lightning stroke at node 11(Chandraghona) there is possibility of voltage build up at adjacent nodes 9(Feni), 10(Madanhat), 11(Chandraghona) and 12(Kaptai). This happens because waves reflected from nearby open end nodes Kaptai and Sikalbaha add up. The peak value of voltage at nodes 9(Feni), 10(Madanhat), 11(Chandraghona) and 12(Kaptai) are 1.34 p.u., 2.60 p.u., 2.0 p.u. and 1.76 p.u. respectively. Only the surge voltage wave at node 10(Madanhat) is shown in fig. 4.11. All the reflected wave from open end nodes 12(Kaptai) and 13(Sikalbaha) add up with the transmitted wave at node 10(Madanhat). The peak of 2.60 p.u. occurs at 269 microseconds after the stroke at Chandraghona. Loading the system at node 6(Ghorasal) changes the wave shape at the nodes a bit but the peak value remains the same. This is because node 6(Ghorasal) is far away from the nodes under study. Connecting a load at node 12(Kaptai) damps the wave shape. This is because the reflection coefficient at node 12(Kaptai) is no longer 2 but less than 1.

For a single lightning stroke at node 7(Siddhirganj) there is possibility of voltage build up at adjacent nodes 7(Siddhirganj), 6(Ghorasal), 8(Comilla), 14(Ullon) and 15(Tongi) under no load and load at nodes 6(Ghorasal) and 12(Kaptai) conditions. This is because reflection from open end node Tongi contributes mostly. In Fig. 4.13 surge voltage wave at node 14(Ullon) is shown. The peak has a value of 2.21 p.u. at 191 micro seconds, which is the superposition of reflected wave from node 15(Tongi) with transmitted wave from node 7(Siddhirganj).

For a single lightning stroke at node 8(Comilla) there is possibility of voltage build up at some adjecent nodes under no load and load at nodes 6(Ghorasal) and 12(Kaptai) condition. At nodes 8(Comilla), 9(Feni) and 7(Siddhirganj) the peak values are around 1 p.u. for all three load conditions. At nodes 14(Ullon) and 15(Tongi) the peak has a value of around 2 p.u. This can be explained as node 14(Ullon) is only 12.8 miles away from open end node 15(Tongi).

5.5 Analysis of Multiple Strokes at Different Nodes

From the analysis of function and time for all nodes for stroke at different nodes it is observed that at some nodes possibility of voltage build up exist, if multiple lightning stroke occur. Multiple (two) strokes of 500 and 1500 microseconds are considered.

For multiple lightning stroke at node 1(Sylhet) there is possibility of voltage build up at node 6(Ghorasal) for no load condition. The surge voltage wave at Ghorasal for 500 micro seconds interval is shown in Fig. 4.15. The first stroke reaches

Ghorasal at 716 micro seconds and the reflected wave from open end node Tongi reaches at 1262 micro seconds with 1 p.u. and 0.99 p.u. magnitude respectively. The second stroke at 500 micro seconds after first stroke reaches Ghorasal at 1216 micro seconds (716 + 500 = 1216) with 1. p.u. magnitude. This adds up with the wave reflected from Tongi and the value reaches 1.51 p.u. magnitude at 1263 micro seconds after the first stroke. With load at node 6(Ghorasal) there is no possibility of build up. With load connected at node 12(Kaptai) the reflected wave from far end diminishes (Fig. 4.17) but the peak value remains unchanged. This is because far end nodes has less significant i.e. the wave diminishes much before it reaches the desired node. The surge voltage wave at node 3(Srimangal) for repeated stroke of 1500 micro seconds interval at node 1(Sylhet) under load at node 12(Kaptai) condition is shown in Fig. 4.16 . The peak has a value of 1.41 p.u. magnitude.

With multiple stroke (1500 micro seconds interval) at node 12(Kaptai) there is possibility of voltage build up nodes 8(Comilla) and 9(Feni) under no load and load at node 12(Kaptai) condition. In both conditionsthe peak value (1.28 p.u.) remains the same but the wave shape is different (Fig. 4.19 (a) and (b)).

For multiple stroke at node 11(Chandraghona) there is no possibility of voltage build up at adjacent nodes.

For multiple stroke at node 7(Siddhirganj) there is voltage build up at adjacent nodes.

For repeated stroke of 150 micro-seconds interval at node 8 (Comilla) there is possibility of voltage build up at nodes 7(Siddhirganj), 8(Comilla) and 9(Feni) for all three load conditions. In Fig. 4.20 surge voltages at node 7(Siddhirganj) and 8(Comilla) are shown. In Fig. 4.21 surge voltage wave at node 9(Feni) is shown.

5.6 Analysis of Fully Loaded System

The system is loaded according to loads shown in Table-2 (Page-47). All the studies are made under this condition. The effect is that peak values at all the nodes diminishes very much.

5.7 Analysis of Study with Artificial Reactor at Node 14(Ullon)

When a artificial reactor is connected in between node 14(Ullon) and node 15(Tongi), the possibility of voltage build up does not change much. This is because change in values of transmission and reflection coefficients are supersed by presence of open end node 15(Tongi) only 12.8 miles away.

CHAPTER - 6

CONCLUSIONS

6.1 Conclusion

It is observed from the study that for single lightning stroke at end node Sylhet there is possibility of maximum voltage built up at node Ullon for no load as well as load at node Kaptai.

For single lightning stroke at end node Kaptai there is possibility of voltage build up at node Sikalbaha for no load as well as load conditions at Ghorasal or Kaptai.

When single lightning stroke at nodes Chandraghona, Siddhirganj and Comilla are considered there is possibility of voltage build up at nodes adjacent to the disturbed node.

For repeated (two) strokes of 500 micro seconds interval at end nodes Sylhet and Kaptai there is possibility of voltage build up at nodes Ghorasal; Comilla and Kaptai respectively. There is voltage build up possibility at nodes Ghorasal, Comilla and Ullon for repeated strokes of 1500 micro seconds interval at node Siddhirganj. When there is repeated stroke of 1500 micro seconds interval at node Comilla there is voltage build up possibility at nodes Siddhirganj, Comilla and Feni.

When loads are connected at all nodes of the system, the lightning stroke has less significance and voltage build up possibility diminishes appreciably.

6.2 Future Research Area

The complex phenomena of transients due to lightning surges on East Grid of Bangladesh power system has been studied by digital computer. Some of the nodes are identified as dangerous points from operation point of view. This is the second study on lightning surges and the first time a digital computer was used for lightning surge study. This type of study is very important to power engineers of the country as lightning surge causes a few major interruptions each year in East Grid during the Monsoon. Further, more detailed computer studies may be performed. Some of them are:-

(1) Study of lightning surges on a power system using three phase of transmission line rather than single phase.

(2) Study of switching transients on a power system using Bewley's Lattice Method by digital computer. Switching transients may be simulated by digital computer.

(3) Study of lightning surges on a power system considering machine (Generator) transients by digital computer.

(4) Study and investigation into the nature, wave shape and duration of lightning in Bangladesh.

APPENDICES

APPENDIX-A

```
// JOB UET9ISHA
C        PROGRAMME NO. 1
C        CALCULATION OF CO-EFFICIENT AAND B,G AND D
         DIMENSION Z(14),A(15),B(15),G(15),D(15),Y(13)
         READ(1,10)(Z(I),I=1,14)
   10    FORMAT (7F10.3)
         DO 15 I=1,15
         A(I)=0.0
         B(I)=0.0
         G(I)=0.0
   15    D(I)=0.0
         DO 20 I=2,14
         A(I)=(2.*Z(I))/(Z(I)+Z(I-1))
         B(I)=A(I)-1.0
         G(I)=(2.*Z(I-1))/(Z(I-1)+Z(I))
   20    D(I)=G(I)-1.0
         DO 25 I=6,13
   25    Y(I)=1.0/Z(I)
         YY=Y(6)+Y(7)+Y(13)
         YZ=Y(9)+Y(10)+Y(12)
         A(7)=(2.*Y(6))/YY
         B(7)=(Y(6)-Y(7)-Y(13))/YY
         G(7)=(2.*Y(7))/YY
         D(7)=(Y(7)-Y(6)-Y(13))/YY
         A(10)=(2.*Y(9))/YZ
         B(10)=(Y(9)-Y(10)-Y(12))/YZ
         G(10)=(2.*Y(10))/YZ
         D(10)=(Y(10)-Y(9)-Y(12))/YZ
         DO 30 I=12,13
         A(I)=0.0
         B(I)=A(I)+2.0
         G(I)=0.0
   30    D(I)=0.0
         B(15)=2.0
         D(1)=2.0
         D(13)=2.0
         D(15)=2.0
         WRITE(3,35)
   35    FORMAT(1H1,13X,'I',5X,'ALPHA',7X,'BETA',8X,'GAMMA',7X,'DELTA'/)
         WRITE(3,36)(I,A(I),B(I),G(I),D(I),I=1,15)
   36    FORMAT(I15,4F12.6)
         END
// OPTION LINK,LIST
// EXEC FFORTRAN
/*
// EXEC LNKEDT
// EXEC
/*
/&
```

I	ALPHA	BETA	GAMMA	DELTA
1	0.0	0.0	0.0	2.000000
2	0.999575	-0.000425	1.000424	0.000424
3	1.000657	0.000657	0.999342	-0.000658
4	0.997114	-0.002886	1.002885	0.002885
5	1.003277	0.003277	0.996723	-0.003277
6	1.000000	0.0	1.000000	0.0
7	0.631873	-0.368127	0.790193	-0.209807
8	1.113606	0.113606	0.886393	-0.113607
9	0.999450	-0.000550	1.000549	0.000549
10	0.662887	-0.337113	0.666811	-0.333189
11	0.997165	-0.002835	1.002834	0.002834
12	0.0	2.000000	0.0	0.0
13	0.0	2.000000	0.0	2.000000
14	0.964086	-0.035914	1.035913	0.035913
15	0.0	2.000000	0.0	2.000000

```
// JOB UET915HA
// OPTION LINK,LIST
// EXEC FFORTRAN
C       PROGRAMME NO. 2
C       TRANSIENT VOLTAGE AT NODE 2 FOR STROKE AT NODE 1 UNDER DIFFERENT CONDITION
        DIMENSION A(15),B(15),G(15),D(15),IT(15),FF(15),F(4000),RFF(15,4),
       1ITR(15,4),RF(4000)
        READ(1,11)(IT(I),I=1,15)
  110   READ(1,10)(A(I),I=1,15)
        READ(1,10)(B(I),I=1,15)
        READ(1,10)(G(I),I=1,15)
        READ(1,10)(D(I),I=1,15)
   10   FORMAT(8F10.6)
   11   FORMAT(15I5)
        AAA=0.014194
        BBB=6.072014
        VO=1.016471
        DO 80 I=1,4000
   80   F(I)=0.0
        FF(1)=B(1)*D(1)*A(2)
        FF(2)=A(2)
        FF(3)=A(2)*B(3)
        AA=A(2)
        GG=1.0
        DO 20 I=3,11
        AA=AA*A(I)
        GG=GG*G(I)
   20   FF(I+1)=AA*GG*B(I+1)
        FF(13)=(FF(11)*B(13))/B(11)
        FF(14)=(FF(8)*B(14))/B(8)
        FF(15)=(FF(8)*G(14)*B(15)*A(14))/B(8)
C       TRANSIENT VOLTAGE AT NODE TWO FOR STROKE AT NODE ONE
        DO 81 K=1,15
        N=IT(K)
        DO 81 J=1,300
        SS=J
        X=-AAA*SS
        Y=-BBB*SS
        EXX=EXP(X)
        EXY=0.0
        IF(J.LT.7)EXY=EXP(Y)
        V=VO*(EXX-EXY)
        M=N+J
   81   F(M)=F(M)+V*FF(K)
        WRITE(3,35)
   35   FORMAT(1H1,50X,'TRANSIENT VOLTAGE AT NODE TWO'//)
        WRITE(3,36) (I,F(I),I=1,4000,2)
   36   FORMAT(9(I5,F9.4))
C       VOLTAGE WAVE AT NODE TWO WITH REPEATED STROKE OF 500 MSECOND INTERVAL
        DO 23 I=1,4000
   23   RF(I)=F(I)
        DO 24 I=501,4000
   24   F(I)=F(I)+RF(I-500)
        WRITE(3,37)
   37   FORMAT(1H1,30X,'TRANSIENT VOLTAGE AT NODE TWO WITH REPEATED STROKE
       1 OF 500 MICRO SECOND INTERVAL'//)
```

```
      WRITE(3,36)(I,F(I),I=1,4000,2)
C     TRANSIENT VOLTAGE AT NODE TWO WITH FOUR SUCCESSIVE REFLECTIONS
      DO 84 I=1,4000
   84 F(I)=RF(I)
      DO 82 I=1,15
      RFF(I,1)=FF(I)*D(2)
      RFF(I,2)=RFF(I,1)*B(3)
      RFF(I,3)=RFF(I,2)*D(2)
      RFF(I,4)=RFF(I,3)*B(3)
      ITR(I,1)=IT(I)
      ITR(I,2)=IT(I)+328
      ITR(I,3)=ITR(I,2)
      ITR(I,4)=ITR(I,3)+328
   82 CONTINUE
      DO 83 K=1,15
      IF(K.EQ.1) GO TO 83
      DO 83 L=1,4
      N=ITR(K,L)
      IF(N-3700) 120,120,83
  120 DO 83 J=1,300
      SS=J
      X=-AAA*SS
      Y=-BBB*SS
      EXX=EXP(X)
      EXY=0.0
      IF(J.LT.7)EXY=EXP(Y)
      V=V0*(EXX-EXY)
      M=N+J
      F(M)=F(M)+V*RFF(K,L)
   83 CONTINUE
      WRITE(3,38)
   38 FORMAT(1H1,30X,'TRANSIENT VOLTAGE AT NODE TWO WITH FOUR SUCCESSIVE
     1 REFLECTIONS'//)
      WRITE(3,36)(I,F(I),I=1,4000,2)
      GO TO 110
      END
/*
// EXEC LNKEDT
// EXEC
  318   106   434   616  1020 1326 1632 2182 2506 3158 3418 3556 3250 1734 1872
  0.0         0.999976   1.000657  0.997114   1.003277   1.0        0.631873   1.113607
  0.999450    0.662887   0.997165  0.0        0.0        0.964086   0.0
  0.0        -0.000425   0.000657 -0.002886   0.003277   0.0       -0.368128   0.113607
 -0.000550   -0.337113  -0.002835  2.0        2.0       -0.035914   2.0
  0.0         1.000424   0.999342  1.002885   0.996723   1.0        0.790193   0.886393
  1.000549    0.666811   1.002834  0.0        0.0        1.035914   0.0
  2.0         0.000424  -0.000658  0.002885  -0.003277   0.0       -0.209807  -0.113607
  0.000549   -0.333190   0.002834  0.0        2.0        0.035914   2.0
  0.0         0.999976   1.000657  0.997114   1.003277   0.356918   0.631873   1.113607
  0.999450    0.662887   0.997165  0.0        0.0        0.964086   0.0
  0.0        -0.000425   0.000657 -0.002886   0.003277  -0.643082  -0.368128   0.113607
 -0.000550   -0.337113  -0.002835  2.0        2.0       -0.035914   2.0
  0.0         1.000424   0.999342  1.002885   0.996723   0.356918   0.790193   0.886393
  1.000549    0.666811   1.002834  0.0        0.0        1.035914   0.0
  2.0         0.000424  -0.000658  0.002885  -0.003277  -0.643082  -0.209807  -0.113607
  0.000549   -0.333190   0.002834  0.0        2.0        0.035914   2.0
```

```
  0.0        0.999576   1.000657   0.997114   1.003277   1.0        0.631673   1.113607
  0.999450   0.662887   0.997165   0.365748   0.0        0.964086   0.0
  0.0       -0.000425   0.000657  -0.002886   0.003277   0.0       -0.368128   0.113607
 -0.000550  -0.337113  -0.002835  -0.634252   2.0       -0.035914   2.0
  0.0        1.000424   0.999342   1.002885   0.996723   1.0        0.790193   0.886393
  1.000549   0.666811   1.002834   0.0        0.0        1.035914   0.0
  2.0        0.000424  -0.000658   0.002885  -0.003277   0.0       -0.209807  -0.113607
  0.000549  -0.333190   0.002834   0.0        2.0        0.035914   2.0
/*
/&
```

```
C     PROGRAMME NO. 3
C     CALCULATION OF VOLTAGE WAVE AT DIFFERENT NODES WITH SINGLE STROKE
C     AT NODE ONE
      DIMENSION A(15),B(15),G(15),D(15),IT(15),FF(15),JT(14),FF7(15),
     1FF10(15),IT7(15),IT10(15),F(6000)
      READ(1,11)(JT(I),I=1,14)
      READ(1,10)(A(I),I=1,15)
      READ(1,10)(B(I),I=1,15)
      READ(1,10)(G(I),I=1,15)
      READ(1,10)(D(I),I=1,15)
   10 FORMAT(8F10.6)
   11 FORMAT(14I5)
      AAA=6.014194
      BBB=6.073014
      VD=1.016671
C     FUNCTION AND TIME CALCULATION FOR NODE ONE
      NODE=1
      FF(1)=1.0
      FF(2)=B(2)
      AA=1.0
      GG=1.0
      DO 30 I=2,11
      AA=AA*A(I)
      GG=GG*G(I)
   30 FF(I+1)=AA*GG*B(I+1)
      FF(13)=(FF(11)*B(13))/B(11)
      FF(14)=(FF(8)*B(14))/B(8)
      FF(15)=(FF(8)*A(14)*B(15)*G(14))/B(8)
      IT(1)=0
      IT(2)=2*JT(1)
      DO 31 I=3,12
   31 IT(I)=IT(I-1)+2*JT(I-1)
      IT(13)=IT(10)+2*JT(12)
      IT(14)=IT(7)+2*JT(13)
      IT(15)=IT(14)+2*JT(14)
      GO TO 600
C     FUNCTION AND TIME CALCULATION FOR NODE TWO
  601 FF(1)=B(2)*D(1)*A(2)
      FF(2)=A(2)
      FF(3)=A(2)*B(3)
      AA=A(2)
      GG=1.0
      DO 20 I=3,11
      AA=AA*A(I)
      GG=GG*G(I)
   20 FF(I+1)=AA*GG*B(I+1)
      FF(13)=(FF(11)*B(13))/B(11)
      FF(14)=(FF(8)*B(14))/B(8)
      FF(15)=(FF(8)*G(14)*B(15)*A(14))/B(8)
C     FUNCTION AND TIME CALCULATION FOR NODE THREE TO ELEVEN
      IF(NODE-2)102,102,103
  103 FF(NODE)=1.0
      DO 23 J=2,NODE
   23 FF(NODE)=FF(NODE)*A(J)
```

```
      FF(NODE+1)=FF(NODE)*B(NODE+1)
      K=NODE+2
      DO 24 I=K,12
      IF(I.EQ.7) GO TO 115
      FF(I)=(FF(I-1)*A(I-1)*B(I)*G(I-1))/B(I-1)
      GO TO 24
  115 FF(7)=FF(7)/G(NODE)
   24 CONTINUE
      FF(NODE-1)=FF(NODE)*B(NODE)*B(NODE-1)
      L=NODE-2
      DO 25 J=1,L
      I=NODE-1-J
      IF(I.EQ.5) GO TO 116
      FF(I)=(FF(I+1)*G(I+1)*D(I)*A(I+1))/D(I+1)
      GO TO 25
  116 IF(NODE-7)171,171,118
  171 GA=1.0
      GDA=G(6)*D(5)*A(6)
      GO TO 120
  118 DO 5 I=8,NODE
    5 GA=G(I-1)*A(I-1)
  120 FF(5)=FF(NODE)*B(NODE)*GDA*GA
   25 CONTINUE
      IF(NODE-10) 201,201,202
  201 FF(13)=(FF(11)*B(13))/B(11)
      GO TO 205
  202 FF(13)=(FF(10)*G(10)*D(13)*A(10))/D(10)
  205 IF(NODE-7) 206,206,207
  206 FF(14)=(FF(8)*B(14))/B(8)
      FF(15)=(FF(8)*G(14)*B(15)*A(14))/B(8)
      GO TO 102
  207 FF(14)=(FF(7)*G(7)*D(14)*A(7))/D(7)
      FF(15)=(FF(14)*G(14)*D(15)*A(14))/D(14)
C     TIME CALCULATION FOR NODE TWO TO ELEVAN
  102 IT(NODE)=0
      L=NODE-1
      DO 26 J=1,L
   26 IT(NODE)=IT(NODE)+JT(J)
      K=NODE+1
      DO 27 I=K,12
   27 IT(I)=IT(I-1)+2*JT(I-1)
      M=NODE-1
      DO 28 J=1,M
      I=NODE+1-J
   28 IT(I-1)=IT(I)+2*JT(I-1)
      IT(13)=IT(10)+2*JT(12)
      IT(14)=IT(7)+2*JT(13)
      IT(15)=IT(14)+2*JT(14)
C     SEPARATE STORAGE FOR NODE 7 AND 10 FF'S AND TIME
      IF(NODE-7)600,301,303
  303 IF(NODE-10)600,302,600
  301 DO 501 I=1,15
      FF7(I)=FF(I)
  501 IT7(I)=IT(I)
```

```
      GO TO 600
  302 DO 502 I=1,15
      FF10(I)=FF(I)
  502 IT10(I)=IT(I)
      GO TO 600
C     FUNCTION AND TIME CALCULATION FOR NODE TWELVE
  105 NOD=NODE-11
      GO TO (106,107,108,109,110),NOD
  106 FF(12)=A(2)*A(3)*A(4)*A(5)*A(6)*A(7)*A(8)*A(9)*A(10)*A(11)
      FF(11)=FF(12)*B(12)*D(11)
      DO 32 J=1,10
      I=11-J
      IF(I.EQ.5) GO TO 800
      FF(I)=(FF(I+1)*G(I+1)*B(I)*A(I+1))/D(I+1)
      GO TO 32
  800 FF(5)=FF(5)
   32 CONTINUE
      FF(13)=(FF(10)*G(10)*D(13)*A(10))/D(10)
      FF(14)=(FF(7)*G(7)*D(14)*A(7))/D(7)
      FF(15)=(FF(14)*G(14)*D(15)*A(14))/D(14)
      IT(1)=0
      DO 33 I=2,12
   33 IT(I)=IT(I-1)+JT(I-1)
      DO 34 J=1,11
      I=12-J
   34 IT(I)=IT(I+1)+2*JT(I)
      IT(13)=IT(10)+2*JT(12)
      IT(14)=IT(7)+2*JT(13)
      IT(15)=IT(14)+2*JT(14)
      GO TO 600
C     FUNCTION AND TIME CALCULATION FOR NODE THIRTEEN
  107 DO 40 I=1,15
   40 FF(I)=FF10(I)
      FF(11)=FF(11)*G(10)
      FF(12)=FF(12)*G(10)
      FF(13)=FF(10)
      DO 41 I=1,15
   41 IT(I)=IT10(I)+2*JT(12)
      GO TO 600
C     FUNCTION AND TIME CALCULATION FOR NODE FOURTEEN
  108 DO 50 I=1,7
   50 FF(I)=FF7(I)*A(14)
      DO 51 I=8,13
   51 FF(I)=FF7(I)*G(7)*G(14)
      FF(14)=(FF7(14)*A(14))/B(14)
      FF(15)=FF7(15)/G(14)
      DO 52 I=1,13
   52 IT(I)=IT7(I)+2*JT(13)
      IT(14)=IT7(14)-JT(13)
      IT(15)=IT7(15)-JT(13)
      GO TO 600
C     FUNCTION AND TIME CALCULATION FOR NODE FIFTEEN
  109 DO 60 I=1,15
   60 FF(I)=FF(I)
```

```
          DO 61 I=1,14
       61 IT(I)=IT(I)+2*JT(14)
          IT(15)=1TT(7)+JT(13)+JT(14)
      606 DO 84 I=1,6000
       84 F(I)=0.0
          DO 83 K=1,15
          Q=ABS(FF(K))
          IF(Q-0.001)83,83,82
       82 N=IT(K)
          DO 83 J=1,300
          SS=J
          X=-AAA*SS
          Y=-BBB*SS
          EXX=EXP(X)
          EXY=0.0
          IF(J.LT.7)EXY=EXP(Y)
          V=VO*(EXX-EXY)
          M=N+J
          F(M)=F(M)+V*FF(K)
       83 CONTINUE
          WRITE(3,38)NODE
       38 FORMAT(1H1,30X,'TRANSIENT VOLTAGE AT NODE'I4//)
          M=IT(NODE)
          WRITE(3,39)(I,F(I),I=M,5000,2)
       39 FORMAT(9(I5,F9.4))
      306 NODE=NODE+1
          IF(NODE-2)601,601,603
      603 IF(NODE-12)103,105,105
      110 CALL EXIT
          END
```

```
C       PROGRAMME NO. 4
C       CALCULATION OF VOLTAGE WAVE AT DIFFERENT NODES WITH SINGLE STROKE
C       AT NODE TWELVE
        DIMENSION A(15),B(15),G(15),D(15),IT(15),FF(15),JT(14),FF7(15),
       1FF10(15),IT7(15),IT10(15)
        READ(1,11)(JT(I),I=1,14)
        READ(1,10)(A(I),I=1,15)
        READ(1,10)(B(I),I=1,15)
        READ(1,10)(G(I),I=1,15)
        READ(1,10)(D(I),I=1,15)
     10 FORMAT(8F10.6)
     11 FORMAT(14I5)
C       FUNCTION CALCULATION FOR NODE 1 TO 10
        NODE=1
    101 FF(NODE)=1.0
        DO 20 I=NODE,10
     20 FF(NODE)=FF(NODE)*G(I+1)
        FF(NODE+1)=FF(NODE)*D(NODE)*B(NODE+1)
        K=NODE+2
        DO 21 I=K,12
        IF(I.EQ.7)GO TO 5
        FF(I)=(FF(I-1)*A(I-1)*D(I)*G(I-1))/B(I-1)
        GO TO 21
      5 IF(NODE.GT.1)GO TO 6
        FF(7)=FF(NODE)*D(1)*A(2)*A(3)*A(4)*A(5)*A(6)*B(7)*G(6)*G(5)*G(4)*
       1G(3)*G(2)
        GO TO 21
      6 FF(7)=(FF(7)*D(NODE))/(G(NODE)*A(NODE)*G(NODE)*D(NODE-1))
     21 CONTINUE
        IF(NODE.EQ.1)GO TO 25
        FF(NODE-1)=FF(NODE)*G(NODE)*D(NODE-1)*A(NODE)
        IF(NODE.EQ.2)GO TO 25
        L=NODE-2
        DO 24 I=1,L
        J=NODE-1-I
        IF(J.EQ.5)GO TO 23
        FF(J)=(FF(J+1)*G(J+1)*D(J)*A(J+1))/D(J+1)
        GO TO 24
     23 FF(5)=FF(5)*A(NODE)
     24 CONTINUE
     25 FF(13)=(FF(11)*B(13))/B(11)
        IF(NODE-7)206,206,207
    206 FF(14)=(FF(8)*B(14))/B(8)
        FF(15)=(FF(8)*G(14)*B(15)*A(14))/B(8)
        GO TO 102
    207 FF(14)=(FF(7)*G(7)*D(14)*A(7))/D(7)
        FF(15)=(FF(14)*G(14)*D(15)*A(14))/D(14)
C       TIME CALCULATION FOR NODE 1 TC 10
    102 IT(NODE)=0
        DO 30 I=NODE,11
     30 IT(NODE)=IT(NODE)+JT(I)
        K=NODE+1
        DO 31 I=K,12
     31 IT(I)=IT(I-1)+2*JT(I-1)
```

```
          IF(NODE.EQ.1)GO TO 33
          M=NODE-1
          DO 32 J=1,M
          I=NODE+1-J
       32 IT(I-1)=IT(I)+2*JT(I-1)
       33 IT(13)=IT(10)+2*JT(12)
          IT(14)=IT(7)+2*JT(13)
          IT(15)=IT(14)+2*JT(14)
C         SEPARATE STORAGE FOR NODE 7 AND 10 FF'S AND TIME
          IF(NODE-7)500,301,303
      303 IF(NODE-10)500,302,500
      301 DO 501 I=1,15
          FF7(I)=FF(I)
      501 IT7(I)=IT(I)
          GO TO 500
      302 DO 502 I=1,15
          FF10(I)=FF(I)
      502 IT10(I)=IT(I)
          GO TO 500
C         FUNCTION AND TIME CALCULATION FOR NODE 11
      104 NOD=NODE-10
          GO TO (105,106, 107,108,109,110) ,NOD
      105 FF(11)=1.0
          FF(12)=D(11)*B(12)
          FF(10)=G(11)*D(10)*A(11)
          DO 40 J=1,9
          I=10-J
          IF(I.EQ.5) GO TO 200
          FF(I)=(FF(I+1)*G(I+1)*D(I)*A(I+1))/D(I+1)
          GO TO 40
      200 FF(5)=G(11)*G(10)*G(9)*G(8)*G(7)*G(6)*D(5)*A(6)*A(7)*A(8)*A(9)*A
         1(10)*A(11)
       40 CONTINUE
          FF(13)=(FF(10)*G(10)*D(13)*A(10))/D(10)
          FF(14)=(FF(7)*G(7)*D(14)*A(7))/D(7)
          FF(15)=(FF(14)*G(14)*D(15)*A(14))/D(14)
          IT(11)=JT(11)
          IT(12)=3*JT(11)
          DO 41 J=1,10
          I=11-J
       41 IT(I)=IT(I+1)+2*JT(I)
          IT(13)=IT(10)+2*JT(12)
          IT(14)=IT(7)+2*JT(13)
          IT(15)=IT(14)+2*JT(14)
          GO TO 500
C         FUNCTION AND TIME CALCULATION FOR NODE 12
      106 IT(12)=0
          IT(11)=2*JT(11)
          DO 51 I=1,10
       51 IT(I)=IT(I)+JT(11)
          GO TO 500
C         FUNCTION AND TIME CALCUTION FOR NODE 13
      107 DO 60 I=1,15
       60 FF(I)=FF10(I)
```

```
      FF(11)=FF(11)*G(10)
      FF(12)=FF(12)*G(10)
      FF(13)=FF(10)
      DO 61 I=1,15
   61 IT(I)=IT10(I)+2*JT(12)
      GO TO 500
C     FUNCTION AND TIME CALCULATION FOR 14
  108 DO 70 I=1,7
   70 FF(I)=FF7(I)*A(14)
      DO 71 I=8,13
   71 FF(I)=FF7(I)*G(7)*G(14)
      FF(14)=(FF7(14)*A(14))/B(14)
      FF(15)=FF7(15)/G(14)
      DO 72 I=1,13
   72 IT(I)=IT7(I)+2*JT(13)
      IT(14)=IT7(14)-JT(13)
      IT(15)=IT7(15)-JT(13)
      GO TO 500
C     FUNCTION AND TIME CALCUTION FOR NODE 15
  109 DO 80 I=1,15
   80 FF(I)=FF(I)
      DO 81 I=1,14
   81 IT(I)=IT(I)+2*JT(14)
      IT(15)=IT7(7)+JT(13)+JT(14)
  500 WRITE(3,35)NODE
   35 FORMAT(//30X,'FUNCTION AND TIME AT NODE'I4//)
      WRITE(3,36)(I,FF(I),IT(I),I=1,15)
   36 FORMAT(3(I10,F10.5,I10))
  306 NODE=NODE+1
      IF(NODE-10)101,101,603
  603 IF(NODE.LT.17)GO TO 104
  110 CALL EXIT
      END
```

```
C     PROGRAMME NO. 5
C     CALCULATION OF FUNCTION AND TIME AT ADJACENT NODE FOR STROKE AT
C     NODE 11,7 AND 8
      DIMENSION A(15),B(15),G(15),D(15),JT(14),FF(16),IT(16),IT7(15),
     1FF7(15)
      READ(1,11)(JT(I),I=1,14)
      READ(1,10)(A(I),I=1,15)
      READ(1,10)(B(I),I=1,15)
      READ(1,10)(G(I),I=1,15)
      READ(1,10)(D(I),I=1,15)
   11 FORMAT(14I5)
   10 FORMAT(8F10.6)
C     STROKE AT NODE 11(CHANDRAGHONA)
C     CALCULATION FOR NODE 9
      NODE=9
      FF(8)=G(10)*G(9)*D(8)*A(9)
      FF(9)=G(10)
      FF(10)=G(10)*D(9)*B(10)
      FF(11)=(FF(10)*A(10)*B(11)*G(10))/B(10)
      FF(12)=(FF(11)*A(11)*B(12)*G(11))/B(11)
      FF(13)=(FF(11)*B(13))/B(11)
      FF(16)=A(11)*B(12)*G(11)*G(10)
      M=7
      IT(9)=JT(10)+JT(9)
      DO 31 I=10,12
   31 IT(I)=IT(I-1)+2*JT(I-1)
      IT(16)=IT(9)+2*JT(11)
      N=8
      GO TO 100
C     CALCULATION FOR NODE 10
  110 NODE=10
      FF(9)=G(10)*D(9)*A(10)
      FF(10)=1.0
      FF(11)=D(10)*B(11)
      FF(12)=D(10)*A(11)*B(12)*G(11)
      FF(13)=G(10)*D(13)*A(10)
      FF(16)=A(11)*B(12)*G(11)
      M=8
      IT(10)=JT(10)
      IT(11)=3*IT(10)
      IT(12)=IT(11)+2*JT(11)
      IT(16)=IT(12)-2*JT(10)
      N=9
      GO TO 100
C     CALCULATION FOR NODE 11
  111 NODE=11
      FF(9)=G(10)*D(9)*A(10)*A(11)
      FF(10)=D(10)*A(11)
      FF(11)=A(11)
      FF(12)=A(11)*B(12)
      FF(13)=G(10)*D(13)*A(10)*A(11)
      FF(16)=0.0
      M=8
      IT(11)=0
```

```
      IT(12)=2*JT(11)
      IT(10)=2*JT(10)
      IT(16)=IT(10)
      N=9
      GO TO 100
C     CALCULATION FOR NODE 12
  112 NODE=12
      FF(10)=A(11)*B(12)*G(11)*D(10)*A(11)
      FF(11)=A(11)*B(12)*D(11)
      FF(12)=A(11)
      FF(13)=(FF(10)*G(10)*D(13)*A(10))/D(10)
      FF(16)=G(10)*A(11)
      M=9
      IT(11)=3*JT(11)
      IT(12)=JT(11)
      IT(16)=2*JT(10)+JT(11)
      N=10
C     COMMON FUNCTION AND TIME CALCULATION
  100 DO 20 I=1,M
      J=M+1-I
      IF(J.EQ.5)GO TO 9
      FF(J)=(FF(J+1)*G(J+1)*D(J)*A(J+1))/D(J+1)
      GO TO 20
    9 FF(5)=(FF(7)*G(7)*G(6)*D(5)*A(6)*A(7))/D(7)
   20 CONTINUE
      FF(14)=(FF(7)*G(7)*D(14)*A(7))/D(7)
      FF(15)=(FF(14)*G(14)*D(15)*A(14))/D(14)
      DO 21 I=1,N
      J=N+1-I
   21 IT(J)=IT(J+1)+2*JT(J)
      IT(13)=IT(10)+2*JT(12)
      IT(14)=IT(7)+2*JT(13)
      IT(15)=IT(14)+2*JT(14)
      WRITE(3,35)NODE
   35 FORMAT(//30X,'FUNCTION AND TIME AT NODE'I4//)
      WRITE(3,36)(I,FF(I),IT(I),I=1,16)
   36 FORMAT(3(I10,F10.5,I10))
      NOD=NODE-8
      GO TO(110,111,112,113),NOD
C     STROKE AT NODE 7(SIDDHIRGANG)
C     CALCULATION FOR NODE 7
  113 NODE=7
      FF(7)=1.0
      FF(8)=B(8)
      FF(9)=A(8)*B(9)*G(8)
      FF(6)=D(6)
      FF(5)=G(6)*D(5)*A(6)*A(7)
      DO 40 I=1,4
   40 FF(I)=(FF(I+1)*G(I+1)*D(I)*A(I+1))/D(I+1)
      DO 41 I=10,12
   41 FF(I)=(FF(I-1)*A(I-1)*B(I)*G(I-1))/D(I-1)
      FF(13)=(FF(10)*A(10)*B(13)*G(10))/B(10)
      FF(14)=D(14)*A(7)
      FF(15)=G(14)*D(15)*A(14)*A(7)
```

```
      IT(7)=0
      IT(8)=2*JT(7)
      DO 42 I=9,12
   42 IT(I)=IT(I-1)+2*JT(I-1)
      IT(6)=2*JT(6)
      DO 43 I=1,5
      J=6-I
   43 IT(J)=IT(J+1)+2*JT(J)
      IT(13)=IT(10)+2*JT(12)
      IT(14)=IT(7)+2*JT(13)
      IT(15)=IT(14)+2*JT(14)
      DO 44 I=1,15
      FF7(I)=FF(I)
   44 IT7(I)=IT(I)
      WRITE(3,35)NODE
      WRITE(3,36)(I,FF(I),IT(I),I=1,15)
C     CALCULATION FOR NODE 6
      NODE=6
      FF(6)=1.0
      FF(7)=D(6)*B(7)
      DO 50 I=1,5
   50 FF(I)=FF7(I)/A(7)
      DO 51 I=8,13
   51 FF(I)=FF7(I)*G(7)
      DO 52 I=14,15
   52 FF(I)=(FF7(I)*G(7))/A(7)
      IT(6)=JT(6)
      IT(7)=3*IT(6)
      DO 53 I=1,5
   53 IT(I)=IT7(I)-JT(6)
      DO 54 I=8,15
   54 IT(I)=IT7(I)+JT(6)
      WRITE(3,35)NODE
      WRITE(3,36)(I,FF(I),IT(I),I=1,15)
C     CALCULATION FOR NODE 8
      NODE=8
      DO 60 I=1,7
   60 FF(I)=FF7(I)*A(8)
      DO 61 I=8,13
   61 FF(I)=FF7(I)/G(8)
      DO 62 I=14,15
   62 FF(I)=FF7(I)*A(8)
      IT(8)=JT(7)
      DO 63 I=1,7
   63 IT(I)=IT7(I)+JT(7)
      DO 64 I=8,13
   64 IT(I)=IT7(I)-JT(7)
      DO 65 I=14,15
   65 IT(I)=IT7(I)+JT(7)
      WRITE(3,35)NODE
      WRITE(3,36)(I,FF(I),IT(I),I=1,15)
C     CALCULATION FOR NODE 14
      NODE=14
      DO 70 I=1,6
```

```
      70 FF(I)=FF7(I)*A(14)
         FF(7)=D(14)*A(7)*G(14)
         DO 71 I=8,13
      71 FF(I)=FF7(I)*G(7)*G(14)
         FF(14)=G(14)
         FF(15)=G(14)*D(15)
         DO 72 I=1,13
      72 IT(I)=IT7(I)+JT(13)
         IT(7)=3*JT(13)
         IT(14)=JT(13)
         IT(15)=IT(14)+2*JT(14)
         WRITE(3,35)NODE
         WRITE(3,36)(I,FF(I),IT(I),I=1,15)
C        CALCULATION FOR NODE 15
         NODE=15
         DO 81 I=1,14
      81 IT(I)=IT(I)+JT(14)
         IT(15)=JT(13)+JT(14)
         WRITE(3,35)NODE
         WRITE(3,36)(I,FF(I),IT(I),I=1,15)
C        STROKE AT NODE 8(COMILLA)
C        CALCULATION FOR NODE 8
         NODE=8
         FF(8)=1.0
         FF(9)=B(9)
         FF(7)=D(7)*A(8)
         FF(6)=G(7)*D(6)*A(7)*A(8)
         FF(5)=G(7)*G(6)*D(5)*A(6)*A(7)*A(8)
         DO 90 I=1,4
         J=9-I
      90 FF(J)=(FF(J+1)*G(J+1)*D(J)*A(J+1))/D(J+1)
         FF(10)=A(9)*B(10)*G(9)
         DO 91 I=11,12
      91 FF(I)=(FF(I-1)*A(I-1)*B(I)*G(I-1))/B(I-1)
         FF(13)=(FF(10)*A(10)*B(13)*G(10))/B(10)
         FF(14)=G(7)*D(14)*A(7)*A(8)
         FF(15)=(FF(14)*G(14)*D(15)*A(14))/D(14)
         IT(8)=0
         IT(9)=2*JT(8)
         IT(7)=2*JT(7)
         N=6
         GO TO 129
C        CALCULATION FOR NODE 9
     132 NODE=9
         DO 120 I=1,15
     120 FF(I)=FF(I)*A(9)
         FF(8)=B(9)*D(8)*A(9)
         FF(9)=A(9)
         DO 121 I=10,13
     121 FF(I)=FF(I)/(G(9)*A(9))
         IT(9)=JT(8)
         IT(8)=3*JT(8)
         N=7
         GO TO 129
```

```
      C     COMMON CALCULATION FOR NODE 8 AND 9
        129 DO 130 I=1,N
            J=N+1-I
        130 IT(J)=IT(J+1)+2*JT(J)
            DO 131 I=10,12
        131 IT(I)=IT(I-1)+2*JT(I-1)
            IT(13)=IT(10)+2*JT(12)
            IT(14)=IT(7)+2*JT(13)
            IT(15)=IT(14)+2*JT(14)
            WRITE(3,35)NODE
            WRITE(3,36)(I,FF(I),IT(I),I=1,15)
            IF(NODE.EQ.9)GO TO 140
            GO TO 132
      C     CALCULATION FOR NODE 7
        140 NODE=7
            FF(7)=1.0
            FF(8)=D(7)*B(8)
            FF(9)=B(9)*G(8)
            FF(10)=A(9)*B(10)*G(9)*G(8)
            DO 141 I=11,12
        141 FF(I)=(FF(I-1)*A(I-1)*B(I)*G(I-1))/B(I-1)
            FF(13)=(FF(10)*A(10)*B(13)*G(10))/B(10)
            DO 142 I=14,15
        142 FF(I)=FF(I)/(A(8)*A(9))
            FF(6)=G(7)*D(6)*A(7)
            FF(5)=G(7)*G(6)*D(5)*A(6)*A(7)
            DO 143 I=1,4
            J=5-I
        143 FF(J)=(FF(J+1)*G(J+1)*D(J)*A(J+1))/D(J+1)
            IT(7)=JT(7)
            IT(8)=3*JT(7)
            IT(9)=2*JT(8)+JT(7)
            DO 144 I=10,12
        144 IT(I)=IT(I-1)+2*JT(I-1)
            IT(6)=2*JT(6)+JT(7)
            DO 145 I=1,5
            J=6-I
        145 IT(J)=IT(J+1)+2*JT(J)
            IT(13)=IT(10)+2*JT(12)
            IT(14)=JT(7)+2*JT(13)
            IT(15)=IT(14)+2*JT(14)
            WRITE(3,35)NODE
            WRITE(3,36)(I,FF(I),IT(I),I=1,15)
      C     CALCULATION FOR NODE 14
            NODE=14
            DO 150 I=1,6
        150 FF(I)=FF(I)*A(7)*A(14)
            DO 151 I=8,13
        151 FF(I)=FF(I)*G(7)*G(14)
            FF(7)=D(14)*A(7)*G(14)
            FF(14)=A(14)
            FF(15)=A(14)*B(15)
            DO 152 I=1,13
        152 IT(I)=IT(I)+JT(13)
```

```
      IT(7)=3*JT(13)+JT(7)
      IT(14)=JT(13)+JT(7)
      IT(15)=2*JT(14)+JT(13)
      WRITE(3,35)NODE
      WRITE(3,36)(I,FF(I),IT(I),I=1,15)
C     CALCULATION FOR NODE 15
      NODE=15
      DO 160 I=1,14
  160 IT(I)=IT(I)+JT(14)
      IT(15)=JT(13)+JT(14)+JT(7)
      WRITE(3,35)NODE
      WRITE(3,36)(I,FF(I),IT(I),I=1,15)
      END
```

```
// JOB UETS1
// OPTION LINK,LIST
// EXEC FFORTRAN
C       PROGRAMME NO. 6
C       CALCULATION OF VOLTAGE AT DIFFERENT NODE
        DIMENSION FF(15),IT(15),F(4000),RF(4000)
    110 READ(1,10)(FF(I),I=1,15)
        READ(1,11)(IT(I),I=1,15)
     10 FORMAT(8F10.5)
     11 FORMAT(15I5)
        AAA=0.014154
        BBB=6.073014
        VO=1.016671
        DO 84 I=1,4000
     84 F(I)=0.0
        DO 90 K=1,15
        N=IT(K)
        Q=ABS(FF(K))
        IF(Q-0.001)90,90,91
     91 DO 90 J=1,300
        SS=J
        X=-AAA*SS
        Y=-BBB*SS
        EXX=EXP(X)
        EXY=0.0
        IF(J.LT.7)EXY=EXP(Y)
        V=VO*(EXX-EXY)
        M=N+J
        F(M)=F(M)+V*FF(K)
     90 CONTINUE
        WRITE(3,36)(I,F(I),I=1,4000,2)
C       VOLTAGE WAVE AT NODE WITH REPEATED STROKE OF 1500 MICRO SECONDS
C       INTERVAL
        DO 23 I=1,4000
     23 RF(I)=F(I)
        DO 24 I=1501,4000
     24 F(I)=F(I)+RF(I-1500)
        WRITE(3,37)
     37 FORMAT(1H1,30X,'SURGE VOLTAGE AT NODE WITH REPEATED STROKE OF
       1 1500 MICRO SECONDS INTERVAL'//)
        WRITE(3,36)(I,F(I),I=1,4000,2)
     36 FORMAT(11(I5,F7.2))
        GO TO 110
        END
/*
// EXEC LNKEDT
// EXEC
/*
/&
```

APPENDIX-B

Conversion of Line Constants to per Unit (p.u.) and Vice Versa

Voltage, currents, KVA and Impedance in a circuit are often expressed as a percent or per unit of a selected base or reference value of each of these quantities. For instance if a base voltage of 120 KV is chosen, voltages of 108, 120 and 126 KV become 0.90, 1.00 and 1.05 per unit or 90,100 and 105 percent respectively.

The per unit value of any quantity is defined as the ratio of the quantity to its base value expressed as a decimal. The ratio in percent is 100 times the value in per unit.

Voltage, current, KVA and Impedances are so related that selection of base values for any two of them determines the base values of the remaining two. Usually base KVA and base voltage in KV are the quantities selected to specify the base.

For single phase system or three phase systems where the term current refers to line current, the term voltage refers to voltage to neutral and the term KVA refers to KVA per phase, the following formulas relate the various quantities.

$$\text{Base current in Amperes} = \frac{\text{Base KVA}}{\text{Base Voltage in KV}}$$

$$\text{Base Impedance in ohms} = \frac{(\text{Base Voltage in KV})^2}{\text{Base MVA}}$$

Base Power in KW = Base KVA

Base Power in MW = Base MVA

Per Unit (P.u.) Impedence of a cirduit element

$$= \frac{\text{Acutal impedance in ohms}}{\text{Base impedance in ohms}}$$

Since three phase circuits are solved as a single line with a neutral return, the bases for quantities in the impedence diagram are KVA per phase and KV from line to neutral. But data are usually given as total three phase KVA or MVA and line to line KV.

SAMPLE CALCULATION OF ACTUAL VALUES OF R,L and C AT NEW BASE OF 132 V AND 100 VA FROM P.U. VALUES AT 132 KV AND 100 MVA BASE.

Base Impédence Z_b = (base KV)^2/Base MVA ohms.

$$= (132/\sqrt{3})^2/(100/3) = 174.0 \text{ ohms.}$$

Physical ohms = p.u. values x system base ohms.

Physical ohms = p.u. ohms x system base ohms (Y_b) $= \frac{\text{p.u. ohms}}{\text{base } Z_b}$

Physical resistance R in ohms. = p.u. value x 174.0

Physical inductance L in mh $= \frac{\text{p.u. values} \times 174.0 \times 10^3}{314}$

Physical capacitance C in μF $= \frac{\text{p.u. ohms} \times 10^6}{174.0 \times 314}$

1. Tongi-Ullon Section

$$Z_x = (0.0112 + j0.0437) \times 174 = 1.9488 + j7.6030 \ \Omega$$

$$R = 1.95\ \Omega,\ L = \frac{X_L}{w} = \frac{7.6038}{314} = 24.2 \text{ mh}$$

$$b/2 = \frac{j0.0049}{174} = j2.816 \times 10^{-5} \text{mho}$$

$$C/2 = \frac{b/2}{w} \times 10^6\ \mu F = \frac{2.816 \times 10^{-5}}{314} \times 10^6 = 0.09\ \mu F$$

$$\therefore C = 0.18\ \mu F$$

2. Ullon-Siddhirganj Section

$$Z = (0.00835 + j0.0362) \times 174 = 1.452 + j\,6.3\ \Omega$$

$$R = 1.45\,\Omega,\ L = X_L / w = 6.3/314 = 20.8\ mh$$

$$b/2 = j0.00366/174 = j2.105 \times 10^{-5}\,mho,\ C/2 = \frac{2.105\times10^{-5}\times10^{6}}{314}\,\mu F$$

$$= 0.067\ \mu F$$

$$\therefore\ C = 0.134\ \mu F$$

In a similar way parameter values were calculated for all the pye section units.

Travel time is calculated as

The lightning surge wave travels at the speed of light (186,000 miles per sec.). So the wave travel 0.186 miles per micro seconds.

3. Travel time for Ullon - Tongi Section

$$\tau = \frac{12.8}{0.186} = 68.8 \cong 69 \text{ micro seconds.}$$

In a similar way travel time for all sections are calculated and are shown in Table - 1 (Page 34).

APPENDIX- C

Mathematical Expression for a 1/50 Wave

A 1/50 wave is a standard wave used for representing a lightning surge wave. Mathematically it is represented as

$$V(t) = V\,(e^{-t/T_1} - e^{-t/T_2})$$

$$= V\,(e^{-at} - e^{-bt}) \quad \ldots \quad \ldots \quad (1)$$

where a and b are constants whose values are to be found out.

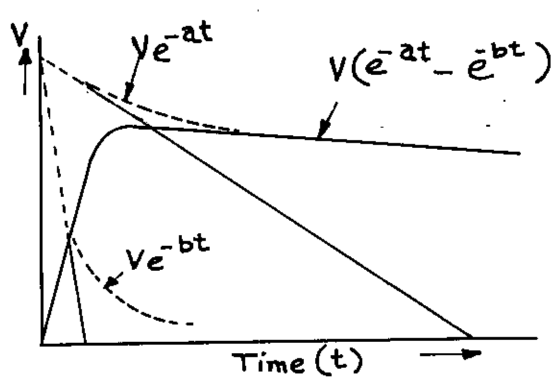


Fig. 7.1 The input surge voltage wave.

$$\frac{dV(t)}{dt} = -aVe^{-at} + bVe^{-bt} = 0$$

$$ae^{-at} = be^{-bt}$$

$$\frac{a}{b} = e^{(a-b)t}$$

$$(a - b)\ t_{max} = \ln\frac{a}{b}$$

$$t_{max} = \frac{1}{a-b}\ \ln\ \frac{a}{b}$$

We have two conditions that the value of V(t) is 1 at 1 micro-second and 0.5 at 50 micro seconds. Putting these values we get,

$$1 = \frac{1}{a-b} \ln \frac{a}{b} \quad \ldots \quad \ldots \quad (2)$$

$$1 = V(e^{-a} - e^{-b}) \quad \ldots \quad \ldots \quad (3)$$

$$0.5 = V(e^{-50a} - e^{-50b}) \quad \ldots \quad \ldots \quad (4)$$

So, we have three e uations with three unknowns to solve

from equation (3) $V = \frac{1}{e^{-a} - e^{-b}}$ ... (5)

from equation (4) $a = -\frac{1}{50} \ln \left(\frac{0.5}{V} + e^{-50b} \right)$ (6)

from equation (2) $b = a - \ln \frac{a}{b}$ ... (7)

To find the solution

1) Assume a and b first.

2) Calculate V from eqn. (5)

3) Find a from eqn. (6)

4) Find b from eqn.(7) with initial value of b. Repeat this step until b converges to a new value.

5) Then repeat from step (2) again.

To have an initial value of a and b we proceed as follow:-

From (3) and (4)

$$2 = \frac{e^{-a} - e^{-b}}{e^{-50a} - e^{-50b}}$$

$$e^{-50b} \simeq 0$$

Let $e^{-b} \simeq 0$

$\therefore\ 2 = e^{49a}$ $\therefore\ a = 0.0141458$

Substitute in (4) $0.5 = Ve^{-50a}$

$\therefore\ V = 1.015$

Putting V in (3), $b = 7.22$

$\therefore$ Let $a = 0.0141458 \simeq 0.01415$

$b = 7.22$, then $V = 1.015$

After a few trials the solution becomes:

$V = 1.0166705$

$a = 0.0141936$

$b = 6.0730136$

and $T_1 = \frac{1}{a} = 70.454209$ micro seconds.

$T_2 = \frac{1}{b} = 0.1646628$ micro seconds.

Check

$$V = V(e^{-at}\ e^{-bt})$$

At 1 micro sec, $V = 1.0166705\left(e^{-\frac{1}{70.454289}} - e^{-\frac{1}{0.1646628}}\right)$

$$= 0.9999999$$

At 50 micro sec, $V = 1.0166705\left(e^{-\frac{50}{70.454289}} - e^{-\frac{50}{0.1646628}}\right)$

$$= 0.5000005$$

So the mathematical expression for a 1/50 wave becomes

$$V(t) = 1.016671\left(e^{-0.014194t} - e^{-6.073014t}\right)$$

and is shown in Fig. 4.1 (page 48.).

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