OVER VOLTAGES IN POWER SYSTEMS

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requirements for the award of the degree
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in
ELECTRICAL ENGINEERING
(Power System Engineering)

By

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February, 1987

CERTIFICATE

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It is to further certify that he has worked for the period from July 1986 to **February,1987**, for preparing this dissertation.

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(KRISHNA JUNG RAYMAJHI)

ABSTRACT

In this dissertation an attempt has been made to calculate the dynamic overvoltage due to sudden load rejection at the receiving-end and switching surge voltage using travelling wave technique.

The various types of overvoltages that may arise on a transmission network are discussed in chapter-I.

The merits and demerits of various methods and techniques for the calculation of switching surge overvoltage, namely, field tests, analog and digital techniques, have been given in chapter-II.

Subsequently an indepth study of dynamic overvoltage and switching surge overvoltage using travelling wave technique have been made for the following conditions:

(a) For dynamic overvoltage
   i) Sudden load rejection
   ii) Shunt componsation
   iii) Switched reactor
   iv) Series compensation

(b) For switching surge overvoltage
   i) Step input
   ii) Sinusaidal input
   iii) Lightning impulse input.

Case study of a system for various condition has been done and simulated on DEC-2050 computer system in FORTRAN-IV (Flow diagram of the program is given in Appendix -I)

The results obtained have been plotted on CALCOM plotter and are given in chapter-VI. The concluding chapter includes the results of the study and their discussion along with the future scope of work in the related field.

CONTENTS

PAGE NO

CERTIFICATE

ACKNOWLEDGEMENT

ABSTRACT

CHAPTER - I INTRODUCTION 1

1.1 TYPES OF OVERVOLTAGES IN POWER SYSTEM 3

1.1.1 External overvoltages 3

1.1.2 Internal overvoltages 4

1.1.2.1 Sustained or stationary over voltages 5

1.1.2.2 Temporary or dynamic overvoltages 5

1.1.2.3 Switching overvoltages 8

CHAPTER - II METHODS OF DETERMINING SWITCHING SURGE OVERVOLTAGES 12

2.1 Field Tests 12

2.2 Analog or Model Method 13

2.2.1 Transient network analyzer 14

2.2.2 Electronic differential analyzer 15

2.3 Digital or Analytical Method 16

2.3.1 Lumped parameter method 18

2.3.2 Fourier transform method 19

2.3.3 Laplace transform method 19

2.3.4 Z-Transform method 20

2.3.5 X-Transform method 21

2.3.6 Schynder-Bergeron method 21

2.3.7 Lattic diagram method 22

CHAPTER- III DYNAMIC OVERVOLTAGES DUE TO SUDDEN LOAD REJECTION 24

3.1 System modelling 24

3.2 Network modelling 25

3.2.1 Model without transformer and generator losses 25

3.2.2 Model with reactor losses 27

3.2.3 Model with transformer losses 28

3.2.4 Model for series compensated line without losses 29

3.3 Method of Solution 31

CHAPTER - IV SWITCHING SURGE OVERVOLTAGE CALCULATION BY TRAVELLING WAVE METHOD 33

4.1 Reflection and refraction of travelling waves. 34

4.2 The travel time array 39

4.3 The reflection coefficient array 40

4.4 Basic time and distance intervals 41

4.5 Solution procedure 42

CHAPTER - V SYSTEM CONSIDERED AND CASES STUDIED 44

5.1 System considered for dynamic overvoltage study 44

5.2 System data 44

5.2.1 Line parameters . 44

5.2.2 Generator parameters 44

5.2.3 Generator transformer parameter 45

5.2.4 Receiving-end transformer 45

5.3 Cases studied 45

5.3.1 Load rejection at the receiving-end 45

5.3.2 With reactors and without transformer and reactor losses 46

5.3.3 With reactor losses 46

5.3.4 With transformer losses 46

5.3.5 Switched reactor 46

5.3.6 Series compensation 47

5.3.7 Variation of shunt compensation 47

5.3.8 Variation of load power factor 47

5.4 System considered for switching surge overvoltage study 47

5.5 System data 48

5.5.1 Line parameters 48

5.6 Cases studied 48

5.6.1 Lightning impulse 48

5.6.2 unit step function 49

5.6.3 Sinusoidal function 49

CHAPTER – VI RESULTS, DISCUSSION & CONCLUSION 50

6.1 Results 50

6.2 Discussion 52

6.3 Conclusion 56

CHAPTER VII FUTURE SCOPE OF WORK 59

REFERENCES

APPENDIX-I

CHAPTER - I

INTRODUCTION

At certain load centers rapid increase in load, much above the power resources available at the near-by regions, necessitates transmission of large bulks of power through long transmission line originating from region rich in power resources. Hence, transmission at higher voltage level has become essential to meet the increasing demand of electrical power efficiently and economically as far as possible.

At the present time there are many systems in use, or coming into use, at 400, 500, 750 and 1100 KV and there is a possibility that still higher voltage will be used in the future. At this order of operating voltage, the cost of insulation forms the major part of the cost of the equipment. Hence, an accurate estimation of the form and magnitude of expected overvoltages on the system has become more and more important with increasing complexity in power systems for an optimum system design.

Once the maximum operating voltage is established, the insulation requirements are basically determined by the overvoltages that can occur in the system. Therefore, the choice of insulation level has a considerable influence on the cost as well as the operating reliability. Large saving in the size and cost of equipment can be affected by adopting reduced insulation levels, especially where EHV and UHV systems are involved. Since, it is very expensive to overinsulate the system to such an extent as to withstand all possible overvoltages that can occur on the system. In fact, EHV and UHV voltage level are economically feasible only if some steps to limit transient overvoltages are incorporated.

Steady-state overvoltages occur but can be controlled by the proper use of regulating transformers and the application of shunt reactors (1). The main causes of transient overvoltages are lightning strikes, surges caused by switching, and surges caused by fault initiation and subsequent clearance. Transient phenomenon is an aperiodic function of time and is of a short duration. The period immediately after the occurance of transient overvoltages is extremely important because during this period circuit components are subjected to greatest stresses from excessive voltages. In extreme case damage to the components of the power system may take place (2).

Thus, for designing a reliable and economical power system network it is important to have an indepth knowledge of various types of overvoltages that can occur in a power system and their effect on the insulation level.

1.1 TYPES OF OVERVOLTAGES IN POWER SYSTEM

Overvoltages on power systems can be brodly classified into two categories, viz., the external or atmospheric overvoltages due to lightning and the internal overvoltages due to various switching operations and fault on the system.

1.1.1 EXTERNAL OVERVOLTAGES :

These are of atmospheric origin and usually take the form of a unidirectional impulse injected into the system due to lightning, whose maximum possible amplitude has no direct relationship to the operating voltage of the system. The energy is fed into the system from the clouds (3).

Lightning is particularly important in high voltage systems operating below 400 KV. Modern investigations in the laboratory as well as in the field on high voltage lines have shown that the most important lightning surges against which apparatus must be protected originate as direct strokes either at the station or on overhead lines leading to the station. The direct strokes may occasionally reach value as high as 2000 KV. They have generally a high rate of voltage rise (100 to 10,000 kV~~amp~~. per micro-second) and high current magnitude (5000 to 200,000 Amp.) which impose severe stresses on the station equipment and may be destructive to protective device (4) .

The frequency of occurance of overvoltage due to thunder storms varies according to the isokeraunic level of the region, their amplitude depending on the presence of earth wires and quality of earthing (5) .

A study of the observations regarding the magnitude of lightning current has shown that currents upto 30 kamp. account for 90 percent of the total number of observations recorded and that currents of the order of 100 kamp exceed for only 1.5 percent of the observations. A value of 30 kamp for the lightning stroke is generally accepted as the criterian for determining the insulation level for high voltage system (4) .

1.1.2 INTERNAL OVERVOLTAGES

These overvoltage originate in the system itself and arise when the state of network is changed by a switching operation or a fault condition. They are a direct consequence of change in the energy associated with the elements of the system (6) .

These overvoltages can also be classified in a different way depending upon their duration and magnitude, as follows :

1.1.2.1 Sustained or Stationary overvoltages (1 - 60 Sec.)

1.1.2.2 Temporary or Dynamic overvoltages (0.03 - 1 sec.)

1.1.2.3 Switching overvoltages (10 - 5000 micro-sec.)

1.1.2.1 SUSTAINED OR STATIONARY OVERVOLTAGES

Overvoltages of system frequency and persisting for some time, perhaps an hour are called stationary overvoltages. These are produced on healthy conductor under sustained earth fault condition on one conductor when the neutral is earthed through an arc supression coil or when the fault resistance is high.

1.1.2.2 TEMPORARY OR DYNAMIC OVERVOLTAGES

Overvoltage of power frequency persisting for few seconds are called dynamic overvoltage. The study of dynamic overvoltages has assumed greater importance in the recent past inview of modern practice of allowing the surge diverter to reseal against dynamic overvoltages exceeding their voltage ratings for a limited duration of time. As the protective level of any surge diverter is proportional to the reseal voltage, the insulation level, and hence cost, of protected high voltage equipment depends indirectly very much on the magnitude and decaying rates of dynamic overvoltages (7).

These overvoltages occur in a power system due to ;

i) Load rejection

ii) Ground Fault

iii) Ferranti - effect

iv) Resonance

v) Ferro-resonance

Rejection of load at the remote end of a long transmission line which initially carries substantial power is a known couse of severe dynamic overvoltages. This problem is very severe when a single line connects an isolated source of generation to a load centre located far-away (4).

In the event of unforeseen load throw-off, though the speed governer and automatic voltage regulator will intervene to restore normal condition, an immediate accelerating torque will be applied to the rotor of the machine so that the machine picks-up speed. Water wheel generator normally overspeed more than steam turbine. The main reason is that, it is not possible for the speed governer to actuate the needle control of a water wheel generator so quickly without damage to the installation due to water hammer action, as compared to the valve of a steam turbine, and there-by reduce the mechanical accelerating torque on the rotor (8) .

Hence, considerably greater speeds are reached for hydro-machines before input and output equilibrium is reached. Thus, the system overvoltages are higher few seconds after load rejection, and the overvoltage at this time determines the choice of the arrestors, which usually are not supposed to operate for such voltages (9) .

Overvoltages are maximum when load dropping occurs in conjuction with single line-to-ground fault on the system, this power frequency overvoltage may exceed the reseal voltage of lightning arrestor.

These overvoltages in a system are caused due to capacitive currents of the unloaded long EHV line flowing through the inductive reactance of generators and transformers supplying the line. This phenomenon is known as Ferranti-effect. The saturation of generator transformer and other interconnected transformers causes ferro-nonlinear oscillation of capacitive energy between capacitance of the line and magnetising inductance of the transformers (7) .

The values of these overvoltages do not 'in practice' depend on the operating voltage but depend only on the length of the line and also on the number of lines terminating at or emanating from a station. The severity on equipments is not only due to the maximum value reached but also due to the repetative nature (10) .

Thus, it is necessary to know the various conditions which gives rise to these overvoltages on the system, inorder to reduce the number of outages and preserve the continuity of service and electric supply.

1.1.2.3 SWITCHING OVERVOLTAGES

Transient overvoltages generated in a system during any switching operation are commonly known as 'switching surges'. These overvoltages are of origin internal to the system and are generally oscillatory in nature and of short duration. Study of switching overvoltage is essential for system operating at higher voltage levels, since the basic insulation levels are determined by switching surges rather than by lightning surges. The basic objectives of switching transient investigations are to identify and quantify transient duties that may arise in a system as a result of intentional and non-intentional switching, and to prescribe economical corrective measures, if necessary (11').

The switching event in a power system initiates the transition between two steady-state conditions, the pre-switching condition and the post switching condition. Thus, a redistribution of energy must occur among the various system elements to change from one steady-state condition to another. This change cannot occur instantly;

a finite period of time, the transient period, prevails during which transient voltages and currents develop to bring about these changes. This causes steep buildup of voltage on transmission lines and other electrical apparatus (11) .

Switching overvoltages arising in power systems have a very wide range of magnitudes and wave-shapes. The transient voltage may be oscillatory wave or a damped oscillatory wave of frequency ranging from few hundred HZ to few KHZ . It may also be considered as a slow rising impulse having a wave front time of 0.1 to 10 ms and tail time of one to several ms. Thus, switching surges contains larger energy than the lightning impulse voltage (4) .

These overvoltages are caused by the following switching operations:

i) Energising of lines on no-loads
ii) Switching-off of long lines on no load
iii) Transformer magnetising currents etc.
iv) Interruption of capacitive currents

The most critical of these switching overvoltages is the one caused by the reclosure of a circuit when there is a trapped charges in the circuit. In the absence of damping and in the most unfavourable case of reclosing, when the applied voltage is at a maximum, the voltage at the open end may reach double the crest value of the phase-to-neutral voltage or even more (4).

The magnitudes of these overvoltages are proportional to operating voltage and can go as high as six times the normal power frequency voltage, particularly in EHV system (8) and depends upon the following factors.

i) Length of the line switched in/out
ii) System fault level at the sending end
iii) instant of closure of circuit breaker poles
iv) Circuit configuration and line termination (7).

Overvoltages originating from more than one of the above causes may occur in rapid succession but only in exceptional cases simultaneously.

There are two components of voltages in a power system during transient period: (i) Fundamental frequency voltages, and (ii) Natural frequency voltages usually of short duration which are superimposed upon the fundamental frequency voltages (2)

System studies have indicated that system configuration has a major effect on the switching overvoltages levels and wave shapes. Thus, generalizations can not easily be made and each system must be studied in detail to explore the severities of these stresses.

In the present work an extensive and exhaustive literature survey has been carried out. The models for the calculation of dynamic overvoltages have been developed. A digital computer program for calculation of dynamic & switching overvoltage transients, using travelling wave technique has also been developed. The study of dynamic overvoltages has been done for a part of the 400 KV system of Dehar, while the switching surge overvoltage study was carried out for an integrated 132 KV NEPAL system.

CHAPTER - II

METHODS OF DETERMINING SWITCHING SURGE OVERVOLTAGES

In earlier days the switching transient overvoltage studies were carried out either by actual tests or by simulating the system by analog means. After the development of TNA, if plays an important role in transient overvoltage studies. But, now a days digital simulation is used for transient overvoltage studies. Various methods have been developed to facilitate digital simulation. Digital computer programmes are becoming increasingly popular, since they are economical and conveient to use.

The method of calculation used should also be capable of representing both lumped and distributed parameters equally well and of faithfully reproducing their variation with frequency. But, in practice such a method is not easily achieved and depends on the specific requirements of the user (12) . The methods for determining these overvoltages in a power system, can be broadly classified as (13) .

2.1 Field Tests
2.2 Analog Model Methods
2.3 Digital or Analytical Methods.

2.1 FIELD TESTS

Some field tests have been reported in the literatures (14,15,16). Field measurements are conducted with stage tests wherein a prescribed sequence of switching operations are conducted for various system operating modes, or they may relate to monitoring day-by-day operating conditions. These are reliable ways of determining the switching surge overvoltages on a line, as they take into account all practical factors that can affect the surges.

In transient switching field measurements, voltage signals are derived from the power circuit via compensated capacitor divider and conveyed to the measuring equipment via shielded co-axial cable. Some times, 'captap' dividers are also used for deriving voltage signals at apparatus bushings provided with capacitance taps or power factor taps (11) .

These tests are conducted on existing or experimental lines, and the surge magnitude and wave shape is recorded. But the extensive field investigations to cover all possible system configurations are very expensive and time consuming. Moreover, the results obtained by field tests on a particular system cannot be generalized for all the systems.

2.2 ANALOG OR MODEL METHOD

The technique is essentially that of designing an electrical model or analog of a dynamic system in such a manner that measurement on the model gives useful information about the actual system. After all model components have been interconnected to properly represent the actual system to be studied, the switching operation is performed.With this model transient voltages and currents can be observed and measured on an oscilloscope or by means of digital metering by connecting measuring probes directly to various locations in the model system (5).The computing tools available for such type of studies are :

1.2.2.1 Transient Network Analyzer (TNA)

1.2.2.2 Electronic Differential Analyzer (EDA)

2.2.1 TRANSIENT NETWORK ANALYZER

The TNA is the most used method of conducting calculated predictions of transient behaviour in a power system. The TNA uses electromagnetic models primarily in representing the system to be studied (11) . The TNA has been and is still the 'work hourse' for the switching transient analysis.

The main purpose of a TNA is to simulate a system with miniature components. The TNA representations of systems can be made with model elements of the same ohmic values as their system counterparts. However, to minimize the number of model elements required for system parameters, other electrical scale factors are introduced in accordance with established theories of modeling (11) . The transient performance of such a model must reasonably duplicate that of the original system.

The accuracy of TNA analysis results depends on the accuracy of data and the degree to which models can be made to approach the desired characteristics.

While representing a system in miniature, the most expensive portion is the transmission **line** model. Other components of a TNA includes the source, switching arrangements, transformer models, lightning arresters, componsating shunt reactors, load etc.

2.2.2 ELECTRONIC DIFFERENTIAL ANALYZER (EDA)

Analog computer, as the name implies, use a physical model equivalent to the given equation and the model is subjected to inputs analogous to the inputs of the given physical system (19) . Perhaps the earliest aids to analysis of power system transients were so-called mechanical defferential analyzers and later the electronic differential analyzer, most commonly called analog computer. These devices assist the solution of differential equations that evolve in mathematical representation of transient phenomena.

This analyzer is well suited for solving electrical transient problems in lumpy circuits, and it is especially attractive for investigations of the effects of varying one or more circuit elements over a range of values. It is not feasible to study switching surge overvoltage of a large system by this method.

2.3 DIGITAL OR ANALYTICAL METHOD

With the development of the digital computer and advanced computer programming techniques, power system problems of the most complex types can be rigorously analyzed. Previously solutions were usually only approximate and errors were introduced by many simplifing assumptions necessary for calculating procedures.

To-day, The digital computer is an indispensible tool in power system planning where it is necessary to predict future growth and simulate day-to-day operations over periods of 20 years or more (10) . Thus, the modern digital computer offers power system engineers a powerful tool to perform more effective studies of any power system.

For switching surge overvoltage determination many computer programs 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 time. 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 the most accurate methods available may not be justified economically because of system data limitations (12) . However, through the use of digital computers these studies can be made with relative ease.

The digital simulation of a physical process is achieved by (i) formulating a mathematical model of the process (ii) computing an approximate solution to the equation. The accuracy of the results obtained depends both on the fidelity of the model and the errors generated by the computation procedure. The various techniques developed for solving the transmission line transient problems are as follows :

2.3.1 Lumped parameter method
2.3.2 Fourier transform method
2.3.3 Laplace transform method
2.3.4 Z - Transform method
2.3.5 X - Transform method
2.3.6 Schynder-Bergeron method
2.3.7 Lattic diagram method

2.3.1 LUMPED PARAMETER METHOD

The traditional method of calculating power system transients has been to use the transient analyser type of analogue computer, which provides facilities for setting up a scale model of the system being studied, using lumped inductance, capacitance and resistance. Overhead lines and cables are represented by artificial lines made up of lumped elements arranged in a series of π sections (12) .

Eventually, with such computers, problems are encountered which are too large to be accommodated without drastic simplification, and one solution to this is to use a digital computer. The differential equations of the individual elements forming the transient analyser representation may be written and solved digitally, Althouth this method is accurate when applied to elements having lumped constants, error is introduced by the representation used for lines and cables. The artificial line used behaves in exactly the same way as the actual line for a particular frequency, but it has a bandwidth which is given approximately by the natural frequency of a π section. If this bandwidth is exceeded by a particular transient the high frequency components are attenuated, introducing error into the solution (12) .

2.3.2 FOURIER TRANSFORM METHOD

The frequency dependance of the parameters of the system can be accommodated by the use of methods based on the Fourier transform. Fundamentally, the method requires the calculation of the response of the system over a range of frequencies and the use of the inverse Fourier transform to transform the response from the frequency domain into the time domain (20) .

In this method, a considerable amount of data and long computation time is required. Since simpler methods are available, whose accuracies are more compatible with the accuracy with which the system data are usually known, the Fourier transform is not considered to be the most suitable method to use for general studies.

2.3.3 LAPLACE TRANSFORM METHOD

This method for solution of travelling waves by Laplace transform has been described by Uram et. al (17) . The Laplace transformation, when applied to terms of an ordinary differential equation, converts the equation into an algebraic equation. In so doing the variable t (time) disappears and a new variable, S (complex frequency), is introduced. The Laplace transform has the added virtue of drawing attention to the initial conditions by providing just enough terms for these conditions to be satisfied. When operated upon this manner the equations of the problem lose their transient aspect and appear more like equations of a steady-state problem in the new variable, S.

2.3.4 Z-TRANSFORM METHOD

In this method, used by Humpage (18) the transmission line forward impulse response and surge impedance function, initially formed in frequency domain, are mapped into Z-plane by bilinear transformation. They are then transformed into time domain, thereafter the formulation is wholly in the time domain and the sequences in solution, to which steps of transformation through the Z-plane lead, are of recursive form. It was found that this transformation is one which introduces a form of distortion error (20). High accuracy in response function definition is achieved over an initial range of frequency beyond which the error progressively increases. This can be achieved by choosing a step length which minimises the error over the frequency range relevant to the electromagnetic transient made of system operation. But this leads to very high computation time.

2.3.5 X-TRSNSFORM METHOD

This method has been used by Raghavan and Sastry (21) for the switching surge overvoltage calculations. In this method reflection and refraction coefficients at all points of discontinuity and surge travel times of different lines are calculated. They are then represented by a block diagram. The transform function of the system is determined with the help of system single flow graph. The surge voltage is found out by carrying an inverse X-Transform. The main drawback of this method is the difficult of inverse X-Transform of complex function.

2.3.6 SCHYNDER-BERGERON METHOD

In this method a relation is established between the voltage and the current at each end of the lines depending upon the voltage and current at the opposite end, including transient time (22) .

Surge propagation is initiated by connecting all sources to the circuit to be energized. The voltage and current is computed at each discrete point for every basic time interval.

The overhead line parameters are in the form of modal surge impedance and attenuation factors are included approximately by introducing series resistance into the modal domain.

2.3.7 LATTICE DIAGRAM METHOD :

This is essentially a graphical method of determining the voltages at any point in a trsnsmission system. Its digital computer adoptation is based on Beuley's (23) lattice diagrams method. The application of this method to single phase representations has been described by Barthold and Carter (24). This method is capable of accomodating any specified input - waveshape, real or complex line terminations, any system configuration. Basically this method is an application of superposition combined with an ingeneious system of book keeping.

In this method, lines and cables are specified by their surge impedances and surge travel times, and the reflected and refracted voltages and currents at junctions and terminations are calculated by the use of reflection and refraction coefficients (25). They have assumed that the incoming wave proceeds through the discontinuity undiminished, but generate a new wave equal to the reflection coefficient at the instant it reaches the discontinuity. This new wave emanates from the discontinuity in both directions, and the sum of the original wave and the newly generated wave represents the total response of the discontinuity to the impinging wave.

In much the same manner, the response of a complex network can be represented as the superposition of the undiminished transmission of the original input plus similar transmission of secondary-wave components generated as the original wave arrives at each bus in the system. The secondary waves produce a third generation of waves; and the process continious to infinitum or until one or both of two criteria is reached. Either the new waves have magnitudes below a specified limit of significance, or they are generated at a time too late to be of interest in a given solution.

Of the methods discussed so far the most commonly used are Schnyder-Bergeron, Fourier Transform, Lattice diagram, and Laplace transform as they are in a more developed stage as compared to other method.

Provided that the same assumptions are made all methods of solution of the transmission-line equations give the same results, although, for a particular type of problem, one method may be more suitable than another. For instance, the Schnyder-Bergeron method is suited to the calculation of voltages and currents at any points in a system, on the other hand, the lattice diagram method is more efficient when the voltages at only one or two points in a large system are required, as for switching transient calculations.

In the present work Lattice diagram method has been used to calculate overvoltages at various nodes of Nepal 132 KV system.

CHAPTER - III

DYNAMIC OVERVOLTAGES DUE TO SUDDEN LOAD REJECTION

In this chapter models have been developed to evaluate the dynamic overvoltages generated in the system due to sudden load rejection.

3.1. SYSTEM MODELLING

A single line diagram of the system considered for the study is shown in Fig. 3.1. It consists of a generator connected to load through a step-up transformer, a series compensated/un-compensated transmission line and an inter-connecting transformer. The single line equivalent circuit used for computer simulation is shown in Fig. 3.2.

It may be noted here, that the representation of transmission network as distributed parameter elements is not necessary for this study as we are not interested in evaluating accurately the transients in the initial period of the order of a few micro-seconds after the disturbance (26). As the transmission network considered is symmetrical, and the load rejection is assumed to take place simultaneously in all the three phases, the single phase equivalent of the system has been used .

Where,

V_1 = Load voltage at 220 KV Bus.

V_2 = Load voltage at 400 KV Bus.

V_3 = Sending end 400 KV Bus-Voltage.

V_4 = Machine terminal voltage.

V_S = Voltage behind transient reactance.

V_C = Voltage across the series capacitor.

X_1 = Leakage reactance of receiving end transformer.

X_2 = Parallel combination of magnetizing reactance of receiving end transformer and shunt reactor, if any.

X_3, X_5 = Capacitive reactance of transmission line assuming, π model.

R_4 = Resistance of transmission line

X_4 = Reactance of transmission line.

X_6 = Parallel combination of magnetising reactance of sending end transformer and shunt reactor, if any.

X_7 = Leakage reactance of sending-end transformer

X_8 = Transient reactance of generator

R_8 = Armature resistance of generator

3.2 NET WORK MODELLING

3.2.1 MODEL WITHOUT TRANSFORMER AND GENERATOR LOSSES :

On load rejection the system reduces to that shown in Fig. 3.3. Now the differential equations for the above

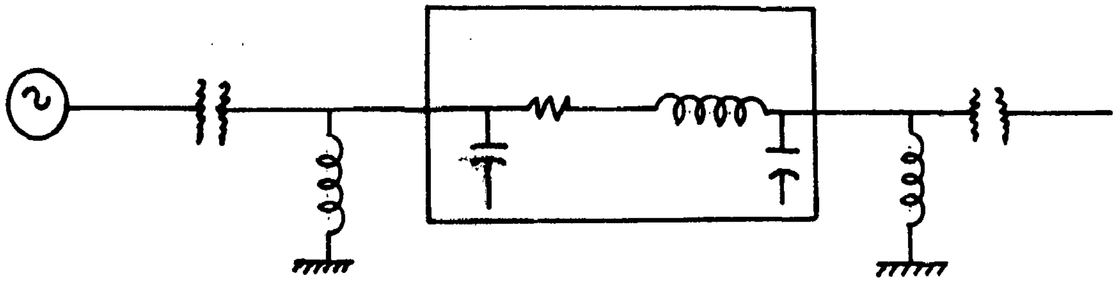


FIG. 3·1 SINGLE LINE DIAGRAM

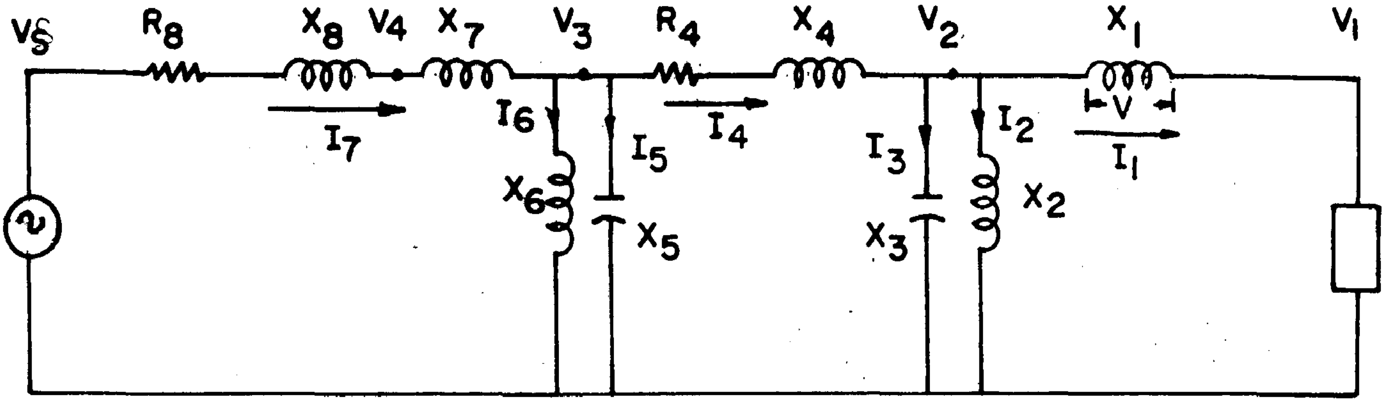
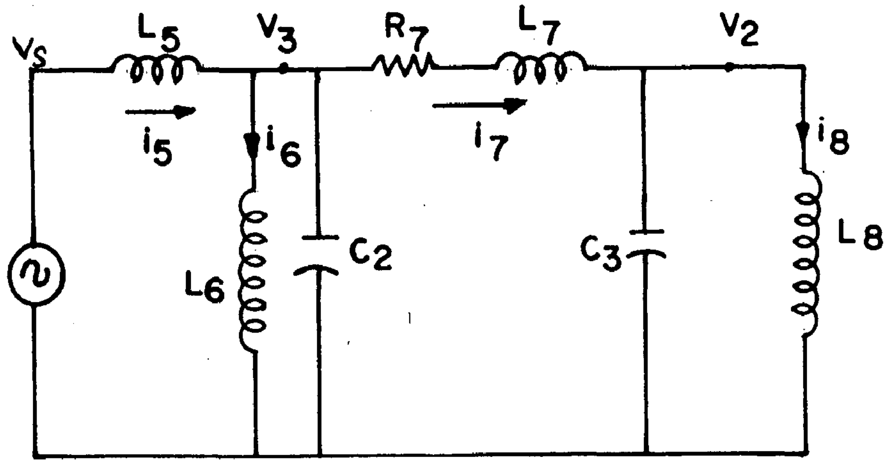


FIG. 3·2 EQUIVALENT CIRCUIT



FIG·3·3 MODEL WITHOUT TRANSFORMER AND GENERATOR LOSSES system (the dot above the various quantities signifies derivative with respect to time) are obtained as follows:

$$\begin{aligned}
i_2 &= C_2\dot{V}_3 = i_5 - i_6 - i_7 \\
i_3 &= C_3\dot{V}_2 = i_7 - i_8 \\
L_5\dot{i}_5 &= V_s - V_3 \\
L_6\dot{i}_6 &= V_3 \\
R_7 i_7 + L_7\dot{i}_7 &= V_3 - V_2 \\
L_8\,\dot{i}_8 &= V_2
\end{aligned} \qquad 3.1$$

These equations can be written as

$$\begin{aligned}
\dot{V}_3 &= \frac{1}{C_2} i_5 - \frac{1}{C_2} i_6 - \frac{1}{C_2} i_7 \\
\dot{V}_2 &= \frac{1}{C_3} i_7 - \frac{1}{C_3} i_8 \\
\dot{i}_5 &= -\frac{1}{L_5} V_3 + \frac{1}{L_5} V_s \\
\dot{i}_6 &= \frac{1}{L_6} V_3 \\
\dot{i}_7 &= \frac{1}{L_7} V_3 - \frac{1}{L_7} V_2 - \frac{R_7}{L_7} i_7 \\
\dot{i}_8 &= \frac{1}{L_8} V_2
\end{aligned} \qquad 3.2$$

In the above first order differential equations V_2, V_3, i_5, i_7, i_6 and i_8 are unknown, source voltage V_s is known.

The above equations (3.1) can also be rearranged in the matrix notation :

$$\begin{bmatrix} \dot{V}_3 \\ \dot{V}_2 \\ \dot{i}_5 \\ \dot{i}_6 \\ \dot{i}_7 \\ \dot{i}_8 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1/C_2 & -1/C_2 & -1/C_2 & 0 \\ 0 & 0 & 0 & 0 & 1/C_3 & -1/C_3 \\ -1/L_5 & 0 & 0 & 0 & 0 & 0 \\ 1/L_6 & 0 & 0 & 0 & 0 & 0 \\ 1/L_7 & -1/L_7 & 0 & 0 & -R_7/L_7 & 0 \\ 0 & 1/L_8 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_3 \\ V_2 \\ i_5 \\ i_6 \\ i_7 \\ i_8 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ V_s/L_5 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad 3.3$$

3.2.2 MODEL WITH REACTOR LOSSES

In case of shunt reactors, the value of L_6 and L_8 depends upon their sizes. The reactance will be paralallel combination of the reactance of transforer and reactor (28).

Similarly, the value of L_5 depends upon the number of machines connected in parallel. When two machine are considered in parallel the value of L_5 would be half the single machine case and so on.

The system configuration is as shown in Fig. 3.4 The equations for this model will be as follows :

$$\begin{aligned}
C_2\overset{o}{V}_3 &= i_5 - i_6 - i_7 \\
C_3\overset{o}{V}_2 &= i_7 - i_8 \\
L_5\overset{o}{i}_5 &= V_s - V_3 - R_5 i_5 \\
L_6\overset{o}{i}_6 &= V_3 - R_6 i_6 \\
L_7\overset{o}{i}_7 &= V_3 - V_2 - R_7 i_7 \\
L_8\overset{o}{i}_8 &= V_2 - R_8 i_8
\end{aligned} \qquad 3.4$$

Rearranging in matrix form :

$$\begin{bmatrix} \overset{o}{V}_3 \\ \overset{o}{V}_2 \\ \overset{o}{i}_5 \\ \overset{o}{i}_6 \\ \overset{o}{i}_7 \\ \overset{o}{i}_8 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{C_2} & -\frac{1}{C_2} & -\frac{1}{C_2} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{C_3} & -\frac{1}{C_3} \\ -\frac{1}{L_5} & 0 & -\frac{R_5}{L_5} & 0 & 0 & 0 \\ \frac{1}{L_6} & 0 & 0 & -\frac{R_6}{L_6} & 0 & 0 \\ \frac{1}{L_7} & -\frac{1}{L_7} & 0 & 0 & -\frac{R_7}{L_7} & 0 \\ 0 & \frac{1}{L_8} & 0 & 0 & 0 & -\frac{R_8}{L_8} \end{bmatrix} \begin{bmatrix} V_3 \\ V_2 \\ i_5 \\ i_6 \\ i_7 \\ i_8 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ V_s/L_5 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad -3.5$$

3.2.3 MODEL WITH TRANSFORMER LOSSES :

In this case, the model is shown in fig. 3.5 and the equation for this model will be as follow :

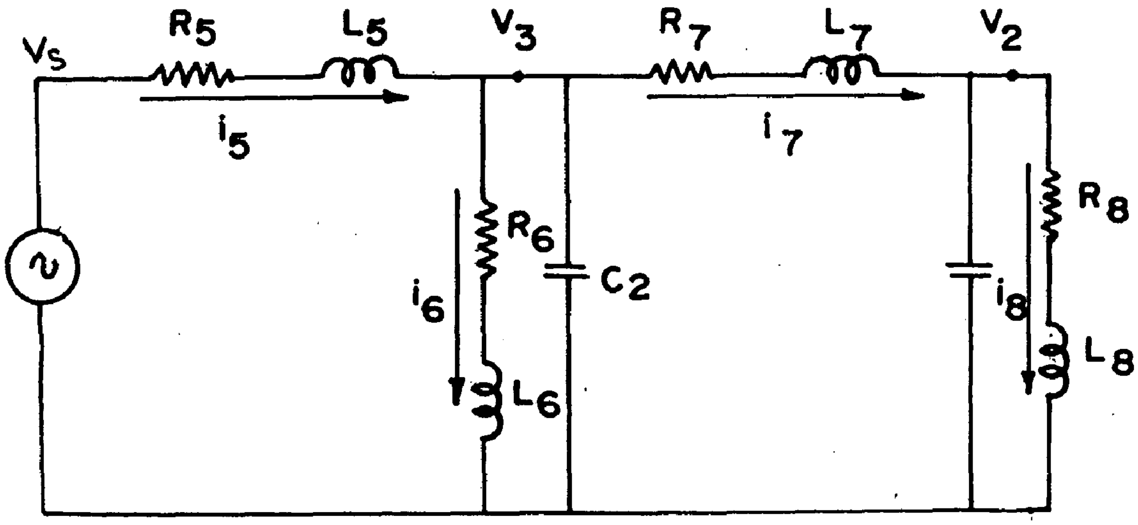
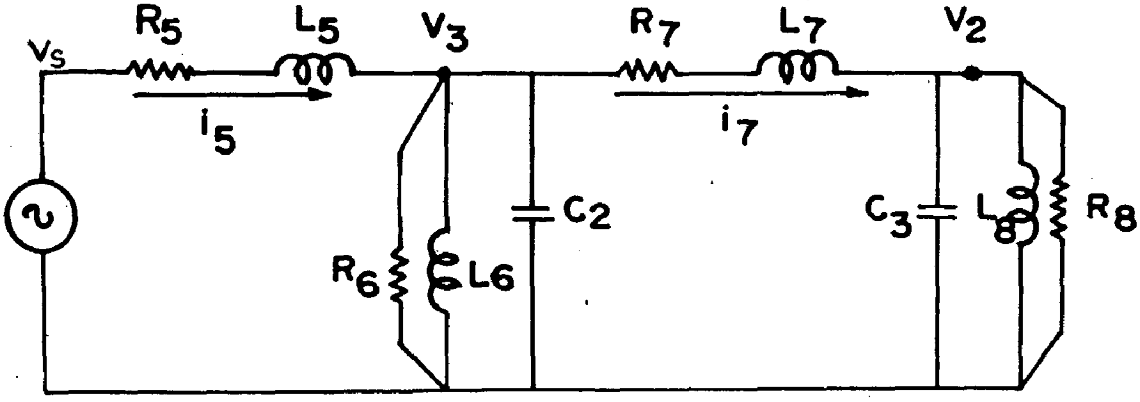


FIG.3·4 MODEL WITH REACTOR LOSSES



FIG·3·5 MODEL WITH TRANSFORMER LOSSES

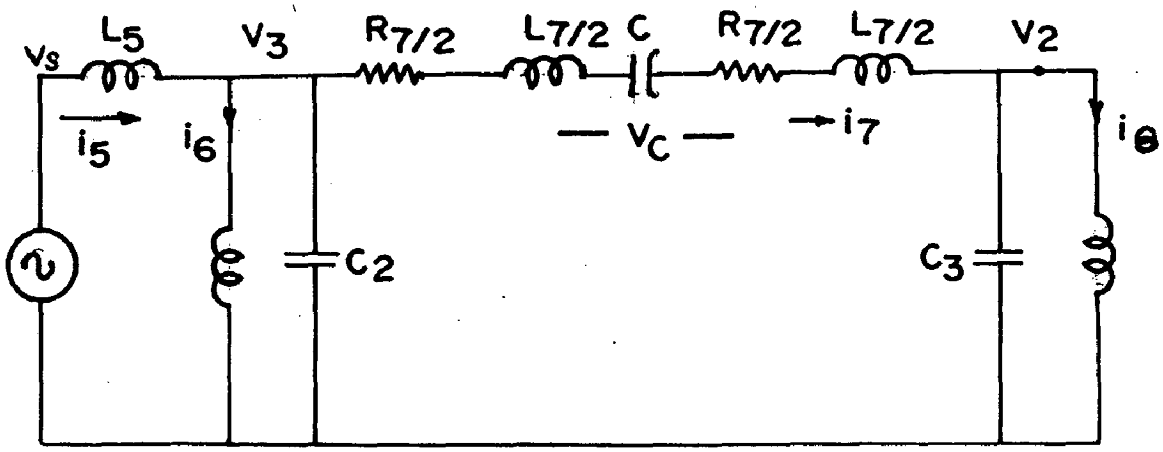


FIG.4·5 MODEL FOR SERIES COMPENSATED LINE

$$
\begin{aligned}
C_2 \dot{V}_3 &= i_5 - V_3/|Z_6| - i_7 \\
C_3 \dot{V}_2 &= i_7 - V_2/|Z_8| \\
L_5 \dot{i}_5 &= V_s - V_3 - R_5 i_5 \qquad\qquad 3.6 \\
L_6 \dot{i}_6 &= V_3 \\
L_7 \dot{i}_7 &= V_3 - V_2 - R_7 i_7 \\
L_8 \dot{i}_8 &= V_2
\end{aligned}
$$

In matrix notation,

$$
\begin{bmatrix} \dot{V}_3 \\ \dot{V}_2 \\ \dot{i}_5 \\ \dot{i}_6 \\ \dot{i}_7 \\ \dot{i}_8 \end{bmatrix}
\begin{bmatrix}
-\frac{1}{C_2|Z_6|} & 0 & \frac{1}{C_2} & 0 & -\frac{1}{C_2} & 0 \\
0 & -\frac{1}{C_3|Z_8|} & 0 & 0 & \frac{1}{C_3} & 0 \\
-\frac{1}{L_5} & 0 & -R_5/L_5 & 0 & 0 & 0 \\
\frac{1}{L_6} & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{L_7} & -\frac{1}{L_7} & 0 & 0 & \frac{R_7}{L_7} & 0 \\
0 & \frac{1}{L_8} & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} V_3 \\ V_2 \\ i_5 \\ i_6 \\ i_7 \\ i_8 \end{bmatrix}
+
\begin{bmatrix} 0 \\ 0 \\ V_s/L_5 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\qquad -3.7
$$

3.2.4 MODEL FOR SERIES COMPONSATED LINE WITHOUT LOSSES :

In this case, static capacitors are connected in series with line conductors and are used to reduce the inductive reactance between the supply point and the load. The major draw back is the high overvoltage produced when a short circuit current flows though the capacitor and special protective should be incorporated.

The factor that effects the overvoltages are :

i) The degree of compensation

ii) The length of line

iii) Circuit configuration of the system etc.

The location of the series capacitor on the transmission line has minor effect on overvoltages. The most important is the degree of series capacitor compensation that determines the value of capacitor voltage, i.e. the choice of the break down voltage of the arrester which protects the capacitor (29).

The system configuration is as shown in Fig.3.6

The equations will be written as follows :

$$\begin{bmatrix} \dot{V}_3 \\ \dot{V}_2 \\ \dot{i}_5 \\ \dot{i}_6 \\ \dot{i}_7 \\ \dot{i}_8 \\ \dot{V}_c \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{C_2} & -\frac{1}{C_2} & -\frac{1}{C_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{C_3} & -\frac{1}{C_3} & 0 \\ -\frac{1}{L_5} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{L_6} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{L_7} & -\frac{1}{L_7} & 0 & 0 & -\frac{R_7}{L_7} & 0 & -\frac{1}{L_7} \\ 0 & \frac{1}{L_8} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{C} & 0 & 0 \end{bmatrix} \begin{bmatrix} V_3 \\ V_2 \\ i_5 \\ i_6 \\ i_7 \\ i_8 \\ V_c \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ V_s/L_5 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad 3.8$$

3.3 METHOD OF SOLUTION

The set of differential equations are numerically solved using Runge - Kutta fourth-order routine for obtaining the time response of state variables. This is one of the most widely used method of numerical solution of differential equations. The advantage of this method over others is a greater accuracy for the same amount of computation. There are several version of kunge-kutta methods, most common one is the fourth-order method (30) .

According to the fourth-order Runge-Kutta, given X_k and the input u_k and $u(k+\frac{1}{2})$. We can compute x_{k+1} from the following relations :

$$x_{k+1} = x_k + 1/6 \ (k_1 + 2k_2 + 2k_3 + k_4) \qquad 3.9$$

where,

k, k_2, k_3 and k_4 are given by

$$\begin{aligned} k_1 &= hf\ (xk,\ uk) \\ k_2 &= hf\ (xk + \tfrac{1}{2}k_1,\ 4(k+\tfrac{1}{2})) \\ k_3 &= hf\ (x_k + \tfrac{1}{2}k_2,\ u(k+\tfrac{1}{2})) \end{aligned} \qquad 3.10$$

and $k_4 = hf\ (x_k + k_3,\ u_{k+1})$

where $(u_{k\ +\frac{1}{2}}) = {}^{u}\text{to} + (k + \frac{1}{2})h$

and h is the step size.

The proposed model has six simultaneous differential equations. These are solved using the basic equation of Runge-Kutta Method (equation 3.9) with a step size of 0.001 sec and for a total time of 0.5 sec.

The flow chart of the developed program is given in Fig. A- I.The results of the studies are given in CHAPTER - VI.

CHAPTER - III

SWITCHING SURGE OVERVOLTAGE CALCULATION BY TRAVELLING WAVE METHOD

In this chapter the details of the switching surge overvoltage calculation method of Barthold and Carter are given.

This is a graphical method of determining the voltages at any point in a transmission system and is an effective way of illustrating the multiple reflections which take place. The method follows the lattice diagram method proposed by L.V. Beuely (23). The application of this method to single phase representations has been described by Barthold and Carter (24). This method is also capable of accommodating any specified inputs wave-shape, real or complex line terminations and any system configuration. Basically, this method is an application of superposition combined with an ingenious system of book keeping (6).

The principle of the method is that, a surge travelling on a line and undergoing reflection at a point of discontinuity, such as bus, gives rise to a reflected and refracted wave which.emanates from the discontinuity in both the directions, and the sum of the original wave and newly generated wave represents the total response of the discontinuity to the impinging wave. The magnitude of these waves are equal to the incident wave times the reflection and refraction coefficients respectively (31) .

4.1 REFLECTION AND REFRACTION OF TRAVELLING WAVES :

It is well known that, there is a strict proportionality between voltage waves on transmission lines and their associated current waves. The proportionality factor is the characteristic impedance Zo of the line. When a wave arives at a discontinuity in a line, where the characteristic impedance of the line changes, some adjustment must occur if this proportionality is not to be violated. This adjustment takes the form of the initiation of two new wave pairs. The reflected voltage wave and its companion current wave travel back down the line superimposed on the incident wave. The refracted wave penetrates beyond the discontinuity. The amplitudes of the reflected and refracted waves are such that the voltage to current porportionalities are preserved for each, as demanded by the characteristic impedances of the lines on which they are travelling (6).

When a line is connected to an underground cable or some equipment such as transformer, it becomes necessary to analyse the condition of wave propagation at such junction.

Consider the junction between lines of characteristic impedances Z_1 and Z_2 and let us suppose that $Z_1 > Z_2$. Suppose that a voltage surge of step function form and magnitude V_1 approaches the junction along the overhead line. The current wave will have the same shape and an amplitude,

$$I_1 = \frac{V_1}{Z_1} \qquad - (4.1)$$

Let the reflected and refracted voltage waves be V_2 and V_3, respectively, so that their currents will be

$$I_2 = -\frac{V_2}{Z_1} \qquad - (4.2)$$

$$I_3 = \frac{V_3}{Z_2} \qquad - (4.3)$$

Note that I_2, because it is travelling in the direction of minus x, has a sign opposite to V_2. If voltage and current are to be continious at the junction, it follows that

$$V_1 + V_2 = V_3 \qquad - (4.4)$$

$$I_1 + I_2 = I_3 \qquad - (4.5)$$

Equation (4.5) can be written by substituting equations (4.2) and (4.3)

$$\frac{V_1}{Z_1} - \frac{V_2}{Z_1} = \frac{V_3}{Z_3} \qquad - (4.6)$$

From equations (4.4) and (4.6) it is possible to write expressions for the reflected and refracted waves in terms of the incident waves.

$$V_2 \left[\frac{Z_2 + Z_1}{Z_2 \times Z_1} \right] = V_1 \left[\frac{Z_2 - Z_1}{Z_2 \times Z_1} \right]$$

$$V_2 = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1} \right] V_1 \qquad - (4.7)$$

The refracted wave is obtained by eliminating V_2 between equation (4.4) and (4.6)

$$V_3 \left[\frac{Z_2 + Z_1}{Z_2 \times Z_1} \right] = \frac{2V_1}{Z_1}$$

$$V_3 = \left[\frac{2\ Z_2}{Z_2 + Z_1} \right] V_1 \qquad - (4.8)$$

The term $\frac{Z_2 - Z_1}{Z_2 + Z_1}$ is called the reflection Coefficient while $(\frac{2\ Z_2}{Z_2 + Z_1})$ is called refraction Coefficient.

$$\text{e.e.} \quad R_r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad - (i)$$

$$\text{and} \quad R_t = \frac{2\ Z_2}{Z_2 + Z_1} \qquad - (ii)$$

Here, Z_1 is the surge impedance of the line along which the surge is incident at the point of discontinuity, and Z_2 is the surge impedance of the outgoing line at the bus. (surge impedances $= \sqrt{L/C}$).

When one or more lines are joined to the line on which the surge originates as shown in Fig. 4.1

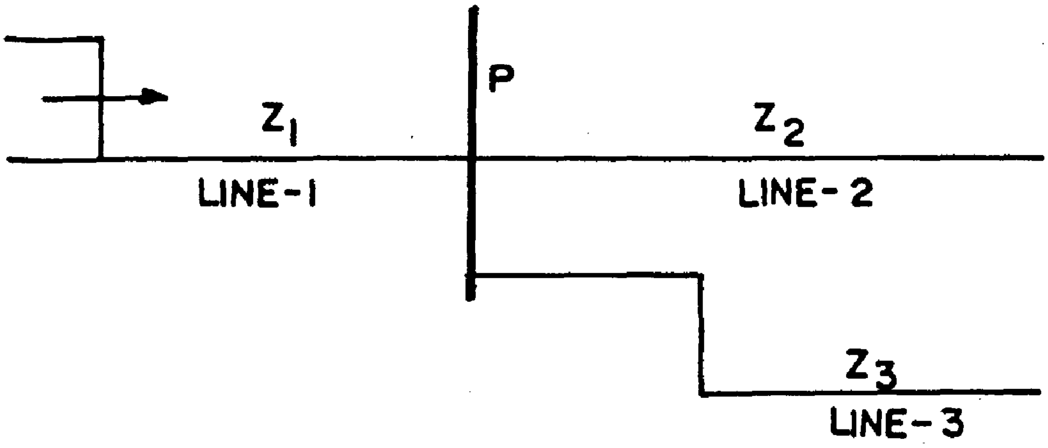

P
Z1
Z2
LINE-1
LINE-2
Z3
LINE-3

FIG. 4.1

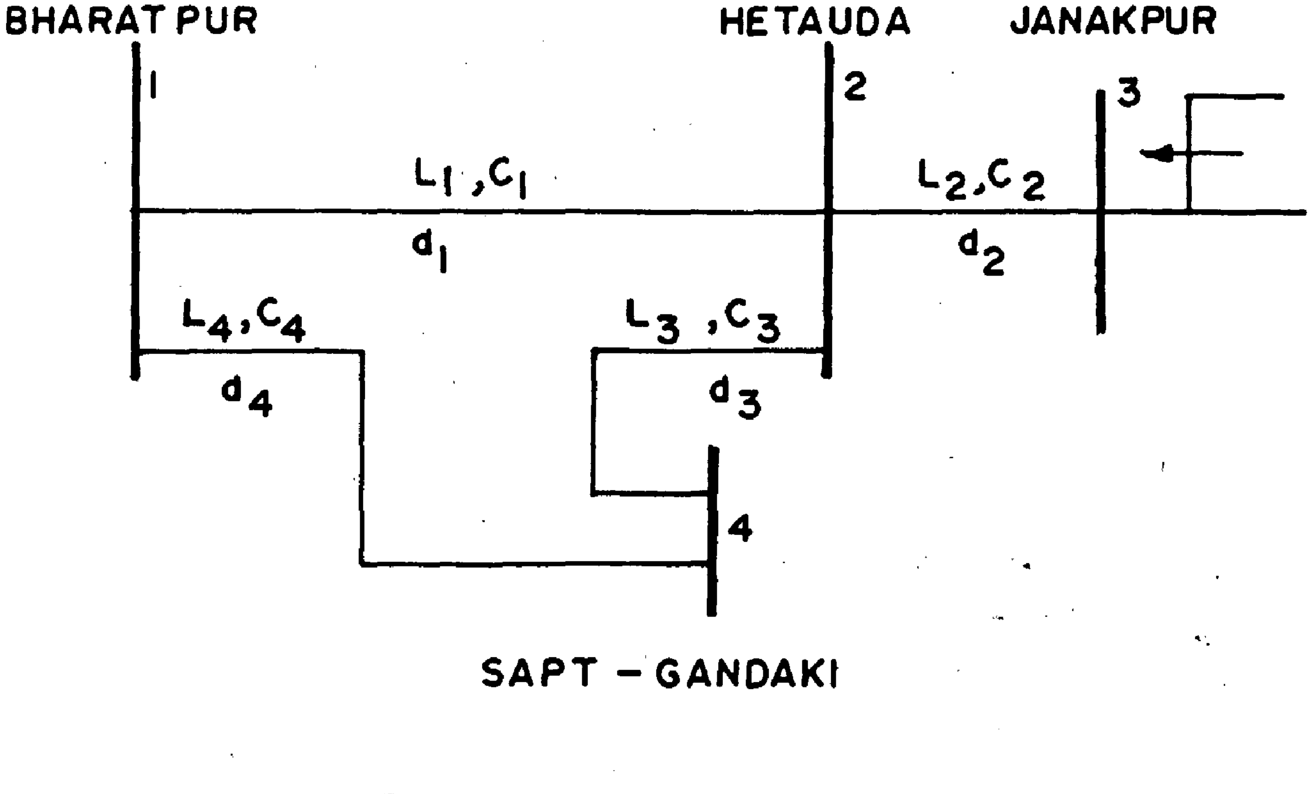

BHARAT PUR
HETAUDA
JANAKPUR
1
2
3
L1, C1
d1
L2, C2
d2
L4, C4
d4
L3, C3
d3
4
SAPT - GANDAKI

FIG. 4.2

The travelling wave when reaches the junction, it sees a change in the impedance.

Let Z_2 and Z_3 be the surge impedances of two lines bused at junction P and the surge impedance of the line on which the wave is incident is Z_1. In this case, Z_2 and Z_3 forms the parallel path for the travelling waves (32).

Therefore, the following relations hold good:

$$\frac{1}{Z_t} = \frac{1}{Z_2} + \frac{1}{Z_3}$$

$$\therefore \quad Z_t = \frac{1}{\frac{1}{Z_2} + \frac{1}{Z_3}}$$

$$\text{Then,} \quad V_3 = \left(\frac{2Z}{Z_t + Z_1}\right) V_1$$

$\therefore$ In this case,

$$R_t = \frac{2Z_t}{Z_t + Z_1} \qquad \text{- (1)}$$

$$\text{and} \quad R_r = \frac{Z_t - Z_1}{Z_t + Z_1} \qquad \text{- (ii)}$$

This is a very important concept upon which the entire calculation is based. It shows that the incident surge travels undiminished beyond the point of discontinuity and in-addition, generated a response wave of magnitude 'R_r' times the incident wave. This response wave, in turn, behaves in the same manner as the incident wave in so far as the system is concerned. This clearly means that for each of the response waves, a new set of secondary waves is generated at all buses, wherever a discontinuity is encountered in its path (23) . The entire computation process, involving the original incident wave and the subsequent train of response waves, continues until.

i) The magnitude of the generated response wave becomes inconsequential, or

ii) its time of generation is of no interest to the system problem under consideration.

Having computed the response waves, the resulting voltage at any bus in the system is obtained as a algebric sum of all waves arriving at the bus prior to the instant of time under consideration (24) .

Since there are a very large number of waves arriving at a bus, both due to the original incident wave and the secondary waves, a systematic recording of the response must be carried out, which can be done on digital computers efficiently.

In the event that two buses are interconnected by more than one electric path, the system is known as 'loop system'. Fig. 4.2 shows a loop system in which there exist more than one electrical path for the surges between 1 and 2. A surge originating at bus 1, for example, can travel to bus 2 either directly by line section 1 - 2, or via bus 4.

In this method, the first step involves the setting up of basic matrices or arrays, which are :

4.2 the travel time array (T) and

4.3 the reflection coefficient array (R_r)

These arrays are matrices of the same order as the number of buses in the system (33) . They are utilized for computing the magnitude and time of generation of the response waves.

4.2 THE TRAVEL TIME ARRAY (T)

The travel time array is formed by calculating the time taken for the surge to travel from any given bus to another to which it is connected. In accordance with the concept described above, the unit wave generated on bus 3 of Fig. 4.2 will arrive undiminished at bus 1,2 and 4 at time equal to travel time from bus 3 to each of these buses. Since, a great many such analysis must be made before a complete solution is reached, it is convenient to define travel time array for the system under study. Such an array is shown in Fig. 4.3 for the system of Fig. 4.2.

The travel time array will also be used to determine the time of arrival of all response waves. In this case, the travel time array gives the times which must be added to the time of origin of a particular response wave to the establish its arrival times, on an absolute time scale, of each other bus in the system.

The travel time array is necessarily symmetrical about the main diagonal. The main diagonal is zero. Since, the travel time for any bus to itself is zero.

4.3 THE REFLECTION COEFFICIENT ARRAY (R_r)

In this case, the initial incident wave in the system of Fig. 4.2 will give rise to a response wave at each bus in the system. The system of origin of these response waves has been established by a travel time array. A similar array for reflection coefficient 'R_r' can be defined to establish the magnitude of the response waves.

Fig. 4.4 shows a reflection coefficient array (R_r) for the system shown in Fig. 4.2. The reflection coefficient array will also be used to establish magnitudes of other response waves in the system. The original magnitude of each wave must be multiplied by the appropriate row of the (R_r) array to give the magnitudes of the next generation of response waves.

The (R_r) array is not symmetrical about its main diagonal. This is because the reflection coefficient depends upon the direction from which the surge is

$$T = \begin{array}{c|cccc} \text{FROM BUS} \backslash \text{TO BUS} & 1 & 2 & 3 & 4 \\ \hline 1 & 0 & T_{12} & T_{13} & T_{14} \\ 2 & T_{21} & 0 & T_{23} & T_{24} \\ 3 & T_{31} & T_{32} & 0 & T_{34} \\ 4 & T_{41} & T_{42} & T_{43} & 0 \end{array}$$

FIG. 4·3

$$R = \begin{array}{c|cccc} \text{FROM BUS} \backslash \text{TO BUS} & 1 & 2 & 3 & 4 \\ \hline 1 & 0 & R_{12} & R_{13} & R_{14} \\ 2 & R_{21} & 0 & R_{23} & R_{24} \\ 3 & R_{31} & R_{32} & 0 & R_{34} \\ 4 & R_{41} & R_{42} & R_{43} & 0 \end{array}$$

FIG. 4·4

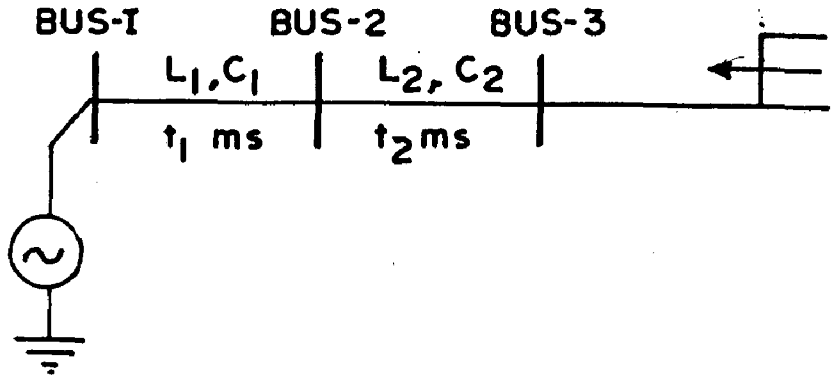


FIG. 4·5

incident at the point of discontinuity. Therefore, when a surge arrives at a bus to which two lines with different surge impedances are connected, the reflection coefficient for two wave incident from the left is different from that for a surge incident from the right. But the main diagonal of the (R_r) array must be assigned a value of zero.

4.4 BASIC TIME AND DISTANCE INTERVALS :

The solution is greatly simplified if time is defined in terms of a constant discrete interval 'T' and if distance intervals are corrospondingly restricted to the product of local velocity and integral multiples of this basic time interval. System response will then be expressed as a function of integral multiples of basic time unit.

If the system consists, as it is generally the case, of a large number of buses interconnected by lines of different lengths, (i.e. with different travel times), a choice has to be made for a basic time interval at which all calculations will be carriedout. This is done in such a way that all the travel times are integral multiples of this basic time interval. A new travel time array, T, is now formed whose elements are obtained by dividing the actual travel times by the basic time.

As an illustration to this consideration, for an example, consider a simple system with 3-buses, with one source-bus and two line sections as shown in Fig. 4.5. Let the actual travel times for the surge on these two lines be $T_{01} = d_1 \sqrt{L_1 C_1}$ and $T_{o2} = d_2 \sqrt{L_2 C_2}$ milliseconds. Where, d_1, d_2 are the lengths of the lines between Buses 1-2 and 2-3, respectively and L_1C_1, L_2C_2 are the Parameter/length of lines.

For this case, the basic unit of time is chosen to be T_B ms (usually T_B = micro-sec.), which gives $T_1 = \frac{T_{01}}{T_B}$ and $T_2 = \frac{T_{o2}}{T_B}$ units for the two travel times in relation to the basic unit of time interval. These are entered in the travel-time array, T, which will be utilized in computation.

This method described is suited to distributed circuit with distributed parameters, but many lumped components such as transformers, shunt reactor and capacitor banks which are found in power system can also be modelled.

4.5 SOLUTION PROCEDURE

In Fig 4.2 Branches are listed both ways in ascending order of the first model number and are referred to under the name Branch. The time taken for a wave to travel along a branch is recorded interms of a positive integer (referred to as period) which converts the basic time unit into actual travel time. Reflection coefficient are stored and referred to as reflect and the corrosponding refraction coefficients obtain, i.e. (1 + Rij)

A surge arriving at node 3 at Time (0) will enter in the branch (3,2), time (0) element of branch time matrix. On arrival at node 2 at time equal to zero plus period (3,2) two waves are generated, on branch (2,1) and branch (2,4) both of magnitude, incident surge magnitude times $(1 + R_{32})$. A reflected wave is also generated on branch (2,3) of magnitude incident surge magnitude times R_{32}. These voltages are entered in the appropriate branch in time (27). On reaching node 1, Time (31), a refracted wave is generated on branch (1,4) and a reflected wave is generated on branch (1,2). This process is continual until a specified time is reached. All transmitted waves for a given node are placed in a separate node time array, a transmitted wave is considered only once even though it could be intered into several branch-time elements.

The method was applied to NEPAL 132KV system and its results along data are given in following chapter.

The flow diagram for the computer program for switching surge overvoltage calculation is given in appendix I..

CHAPTER V

SYSTEM CONSIDERED AND CASES STUDIED

5.1 SYSTEM CONSIDERED FOR DYNAMIC OVERVOLTAGE STUDY

A hydro-electric station with 4 units of 165MW each in stage 1 has been provided at Dehar under Beas project. This power station is connected by a 400 KV single circuit transmission line to Panipat at a distance of 260KM. A study of dynamic overvoltage of this system is done for upto 3 units of 165MW in operation.

5.2 SYSTEM DATA

5.2.1 LINE PARAMETERS :

The line comprises of two conductor bundles per phase and two galvanised steel overhead wires. The line has a delta configuration. The line data is as given below:

$Z_1 = (7.677 + j82.85)$ ohms

$Y_1 = j0.00092349$ mho

5.2.2 GENERATOR PARAMETERS

In these studies the generator has been represented by its sub-transient reactances. Its value is 0.135 p.u on 100 MVA base. In case of two or more generators, the source is represented by the parallel combination of generator and transformer impedances.

5.2.3 GENERATOR TRANSFORMER PARAMETERS

The transformer impedance for 3 x 60MVA, $\frac{11/400}{\sqrt{3}}$ KV transformer has an average value of 15% on 180 MVA base as available from the data. Its value is 0.398 p.u on 100 MVA base.

5.2.4 RECEIVING-END TRANSFORMER

The transformer impedance for 3 x 150 MVA, $\frac{400}{\sqrt{3}}/\frac{200}{\sqrt{3}}$ auto-transformer at the receiving-end has an impedance of 15% on 450 MVA base. Its value is 0.159 p.u on 100 MVA base.

The magnetising current in all the transformers is taken as 0.5% of the rated current.

5.3 CASES STUDIED

In the initial studies, no losses are assumed in reactor and transformers. Of-course this assumption gives rise to overvoltages which are higher than actual value. Therefore lateron, losses can be included to represent a more realistic system.

5.3.1 LOAD REJECTION AT THE RECEIVING-END

In this case three conditions of load rejection are considered as given below:

(i) Load rejection of 150 MW has been assumed for one machine, at power factor 0.85 and 1 p.u receiving-end voltage.

(ii) and (iii) The study of case (i) is again repeated for load rejection of 300 MW and 450 MW for two and three machine respectively.

5.3.2 WITH REACTORS AND WITHOUT TRANSFORMER AND REACTOR LOSSES

In this case, shunt reactors of 50 MVAR and 75 MVAR rating were connected at either end or at both the ends. The study is made seperately for each case.

5.3.3 WITH REACTOR LOSSES

A reactor of 75 MVAR with losses (0.133 p.u) is connected at the receiving-end only.

5.3.4 WITH TRANSFORMER LOSSES

In this case, sending-end transformer loss of 0.046 p.u and receiving transformer with a loss of 0.025 p.u is considered.

5.3.5 SWITCHED REACTOR

In this scheme a reactor of 75 MVAR is connected at receiving-end. This reactor will be switched on to the line 100 ms after the load is rejected. The study is repeated again for switching in reactor after 200 ms.

5.3.6 SERIES COMPENSATION

For the study of series compensated line, a static capacitor of value 18.1983 p.u on 100 MVA base is connected in series with the transmission line.

5.2.7 VARIATION OF SHUNT COMPENSATION

In this case the value of reactor is varied from 10 MVAR to 100 MVAR in steps of 10 MVAR. It is connected at receiving-end only.

5.2.8 VARIATION OF LOAD POWER FACTOR

Load power factor is varied from 0.1 to 1.0 in steps of 0.1 both for lagging and leading cases.

The results of the above studies are tabulated in Table 6.I of the next chapter.

5.4 SYSTEM CONSIDERED FOR SWITCHING SURGE OVERVOLTAGE STUDY

A hydro-electric power station with 3 units of 75 MW each has been provided under Sapt-Gandaki project of Western Nepal. This power station is connected to Bharatpur, Hetauda and Janakpur by a 132 KV single/double circuit transmission lines at a distance of 5KM, 75KM and 212 KM respectively. A study of switching surge overvoltage of this system is done for 3 units of 75 MW in operation, neglecting all line losses.

5.5 SYSTEM DATA

5.5.1 LINE PARAMETERS

The line comprises of single conductor of size 0.20/0.25 sq. in. per phase and one galvanised steel overhead ground wire.

The line data is as given below in Table 5.1

Place to	Place	Volt. (KV)	S.C or D.C.	Condr. (sq.in.)	Length (KM)	on 100 MVA Base X	on 100 MVA Base B
Hetauda	Janakpur	132	D.C	0.25	137	.3088	.0690
Sapt - Gandaki	Hetauda	132	D.C.	0.25	75	.1690	.0378
Hetauda	Bharatpur	132	S.C.	0.20	80	.1845	.0392
Bharatpur	Sapt-Gandaki	132	S.C.	0.25	5	.0113	.0025

Table 5.1 .

5.6 CASES STUDIED

5.6.1 LIGHTNING IMPULSE

In this case a standard lightning impulse of 1.2/50 µs is assumed to strike at node 3 of Fig. 4.2 and overvoltages at different nodes are studied.

5.6.2 UNIT STEP FUNCTION

In the second case a unit step function is applied at node 3 and overvoltages at different-nodes are studied.

5.6.3 SINUSOIDAL FUNCTION

In the third case a sinusoidal voltage wave is applied at node 3 of Fig. 4.2 and again overvoltages of different nodes were studied.

The results of these studies are given in table 6.II of the following chapter.

CHAPTER VI

RESULTS DISCUSSION AND CONCLUSION

6.1 RESULTS

The maximum dynamic and switching surge overvoltage occuring for different cases mentioned in section 5.3 and 5.4 of previous chapter are given in Table 6.I and 6.II respectively.

Table - 6.I

Dynamic Overvoltages

S.No.	Case	Max. Over-voltage p.u	Ref. Fig. No.
1.	Load rejection at receiving end		
	i) when 150 MW load is Thrown-off, at 0.85p.f lagging	3.405	6.1
	ii) when 300 MW load is thrown-off at 0.85 p.f lagging	4.203	6.2
	iii) when 450 MW load is throw-off at 0.85 p.f lagging	4.962	6.3
2.	With reactor and without transformers reactor losses		
	i) 50 MVAR reactor at sending-end only.	2.990	6.4
	ii) 50 MVAR reactor at receiving-end only	2.923	6.5

S.No.	Case	Max. Over-Voltage p.u.	Ref.Fig. No.
	iii) 50 MVAR reactor at both the ends	2.716	6.6
	iv) 75 MVAR reactor at sending end only	2.854	6.7
	v) 75 MVAR reactor at receiving end only	2.787	6.8
	vi) 75 MVAR reactor at both the ends	2.529	6.9
3.	With 75 MVAR reactor at receiving end considering reactor losses	2.650	6.10
4.	Without reactor considering transformer losses	3.210	6.11
5.	Switched reactor of 75 MVAR at receiving end (without losses)		
	i) 100 ms. after load rejection	-	6.12
	ii) 200 ms. after load rejection	-	6.13
6.	Series compensated line, 150MW 0.85 power factor lagging load rejection, without reactor	4.03	6.14
7.	Variation of MVAR values of reactor at receiving end only	-	6.15
8.	Variation of load power factor	-	6.16

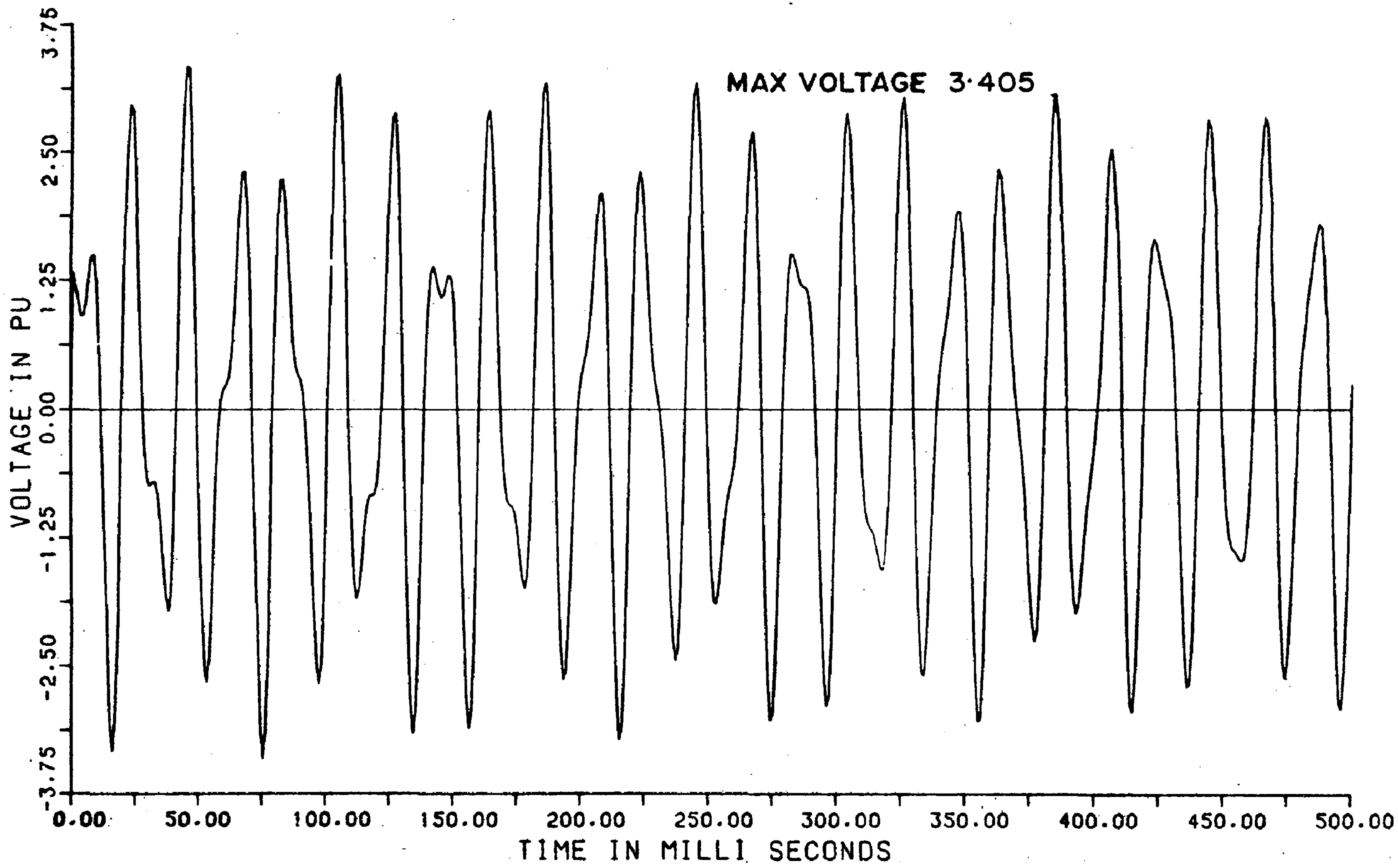
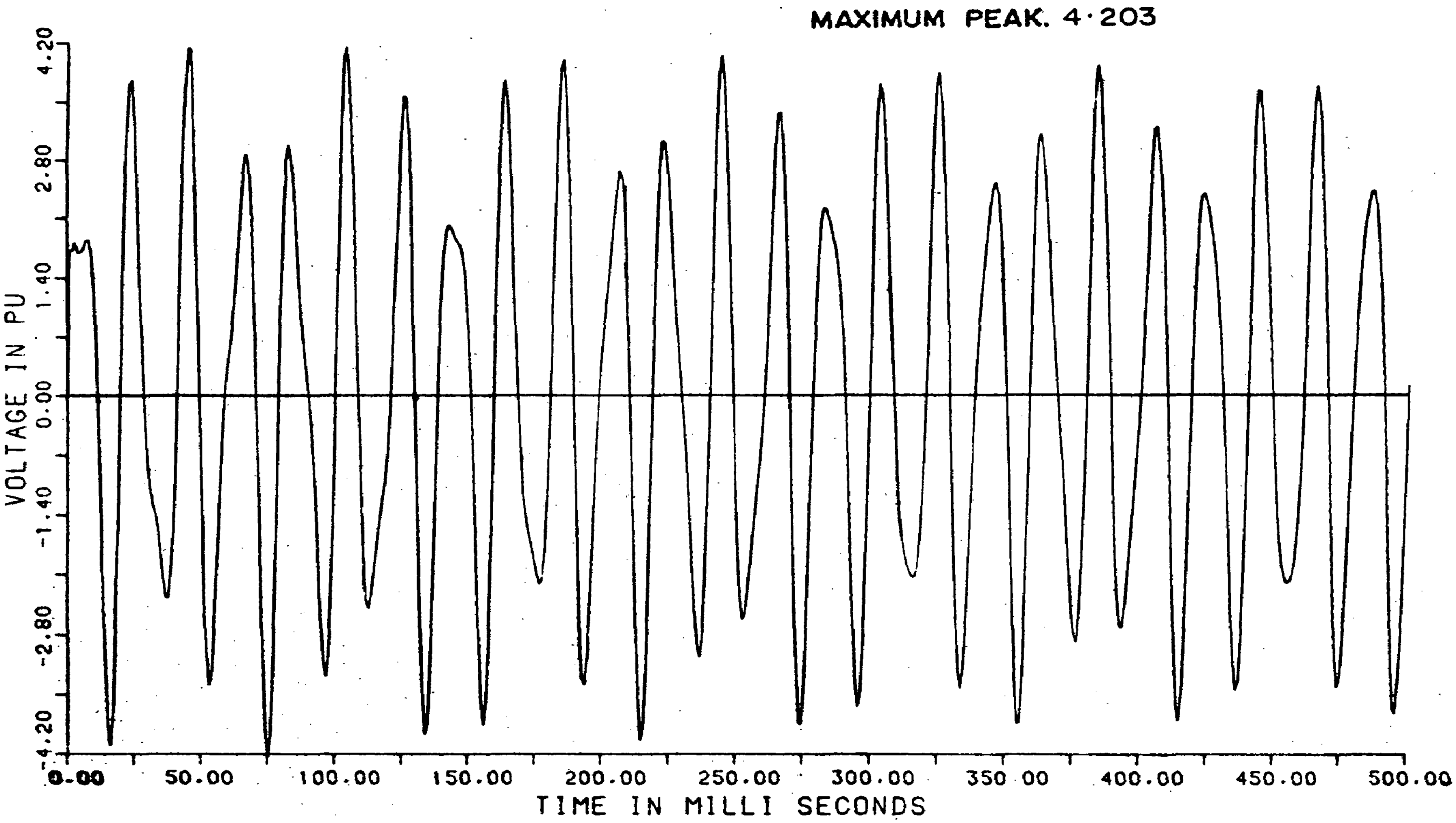


FIG 6·1 DYNAMIC OVERVOLTAGE DUE ·TO SUDDEN LOAD REJECTION

(WITHOUT REACTOR)



MAXIMUM PEAK. 4·203

FIG.6·2 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(WITHOUT REACTOR-D)

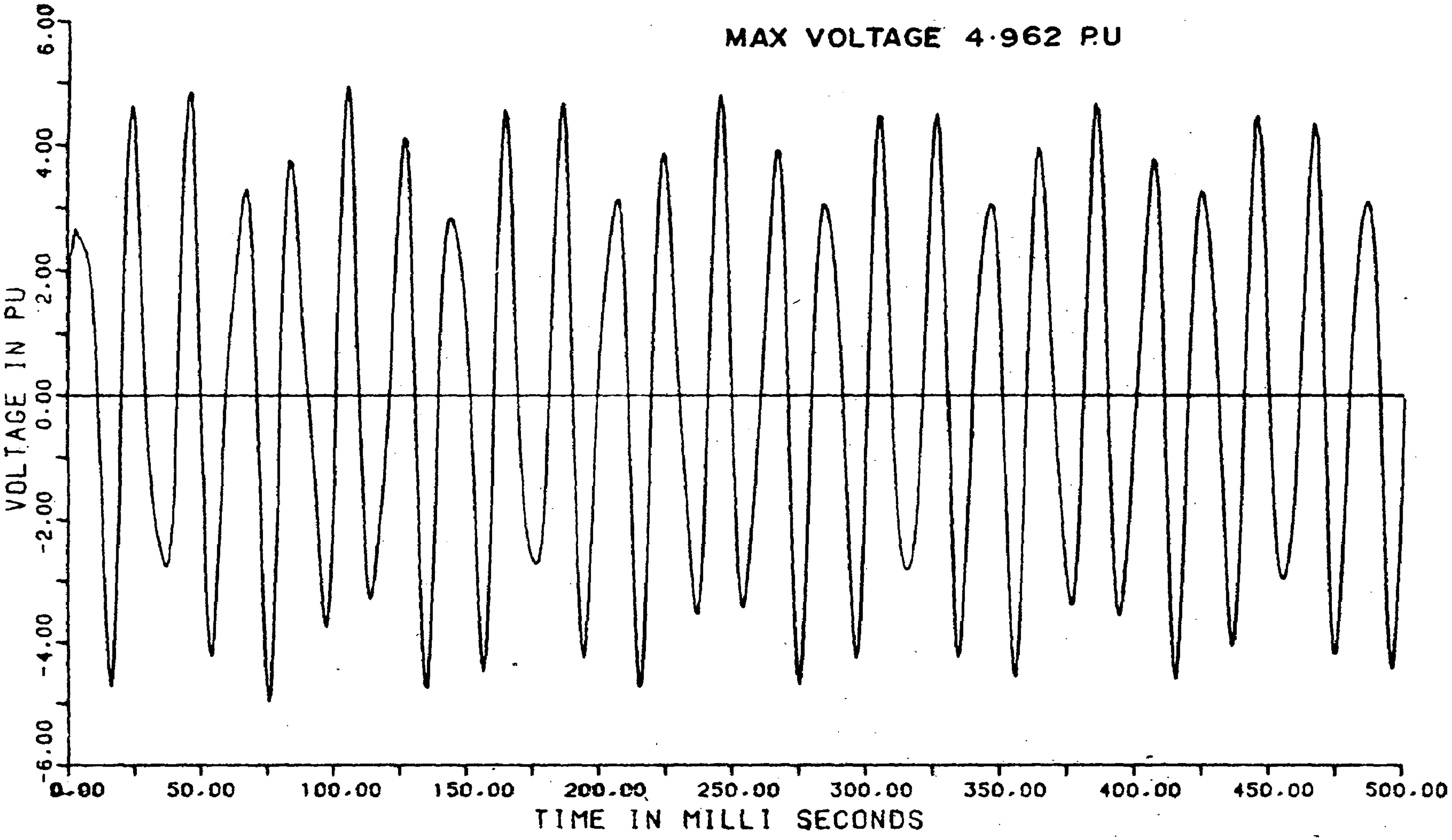


FIG. 6·3 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(WITHOUT REACTOR-T)

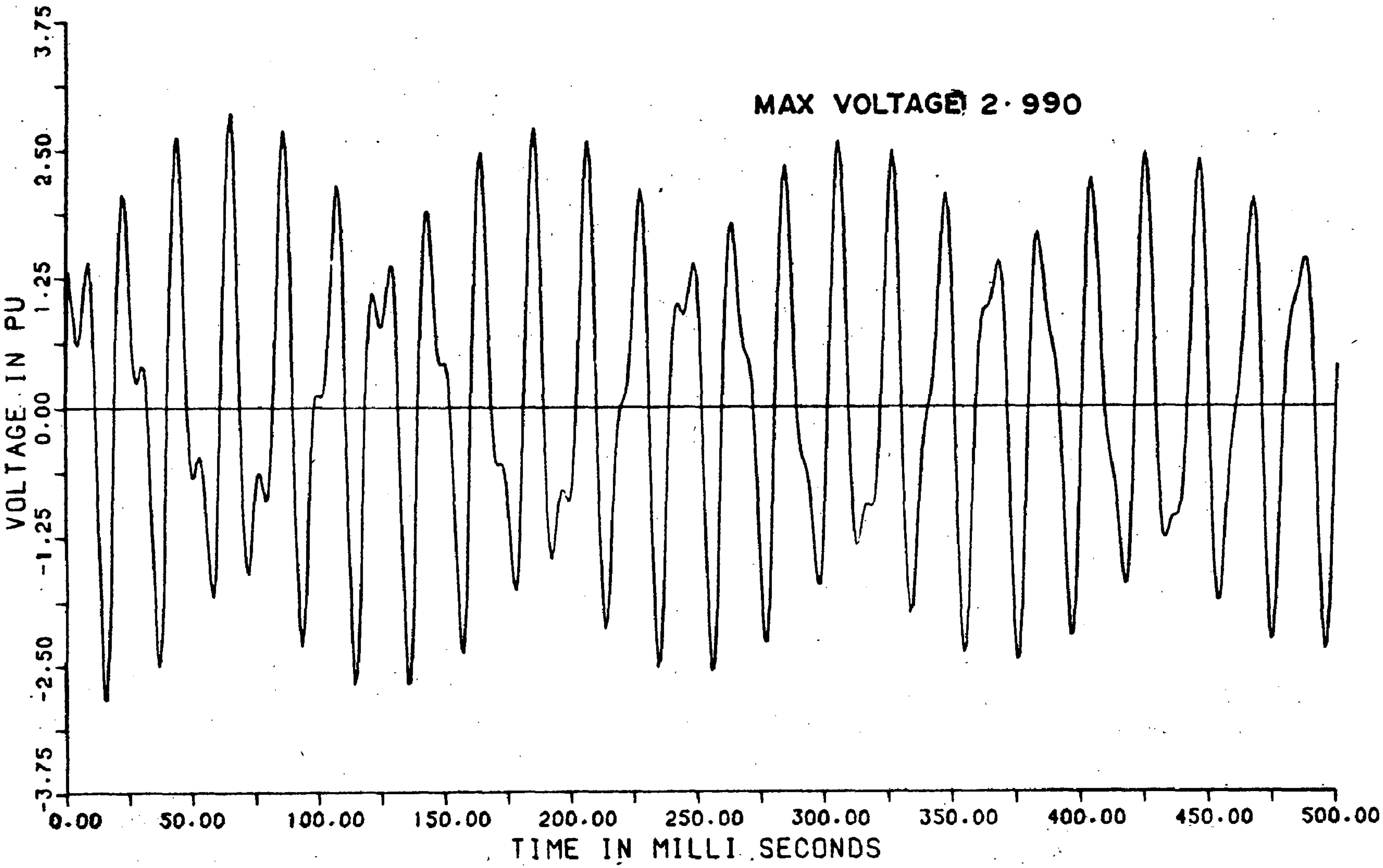


FIG 6·4 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(REACTOR AT SENDING END)

(50 MVAR REACTOR)

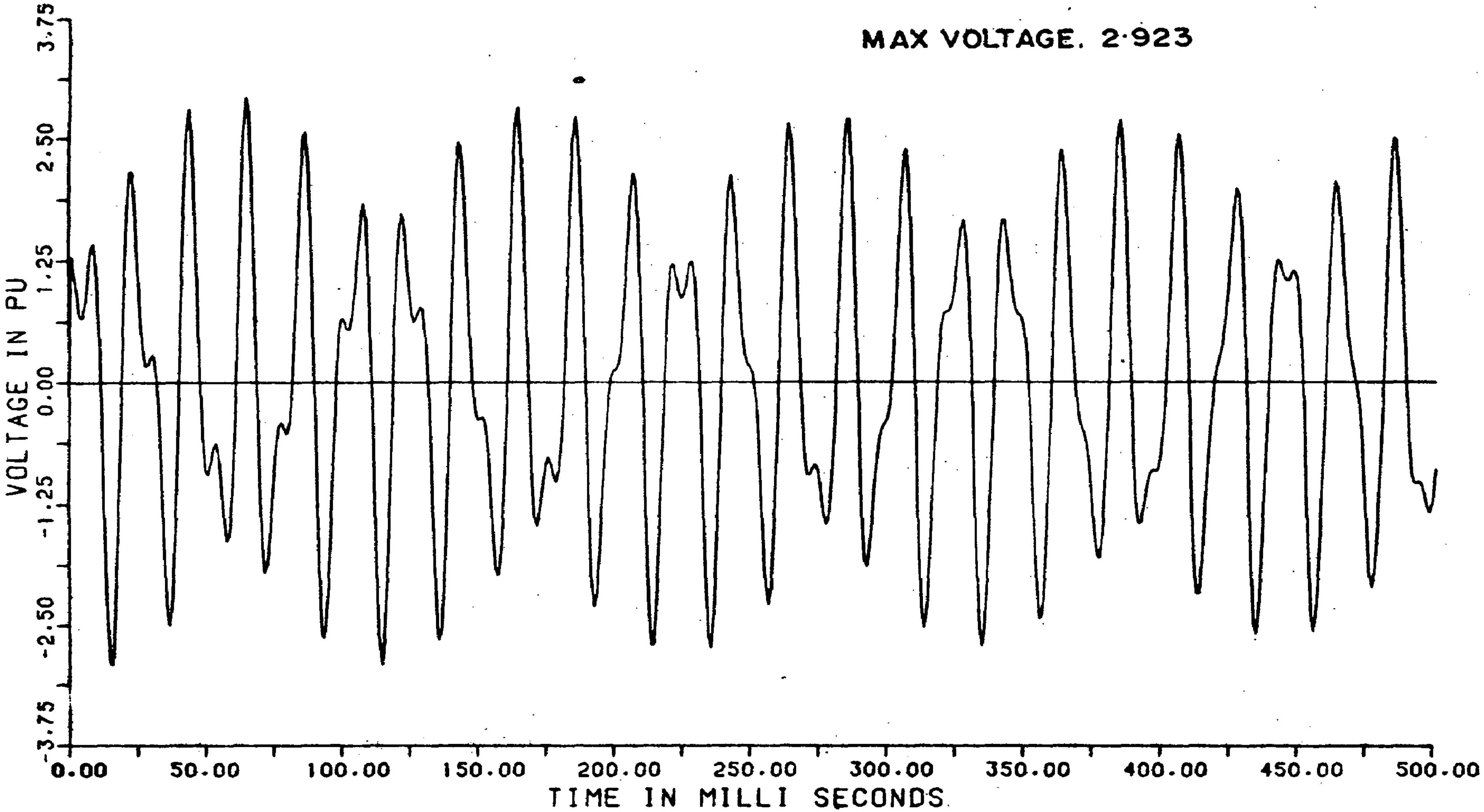


FIG.6.5 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(REACTOR AT RECEIVING END)
(50 MVAR REACTOR)

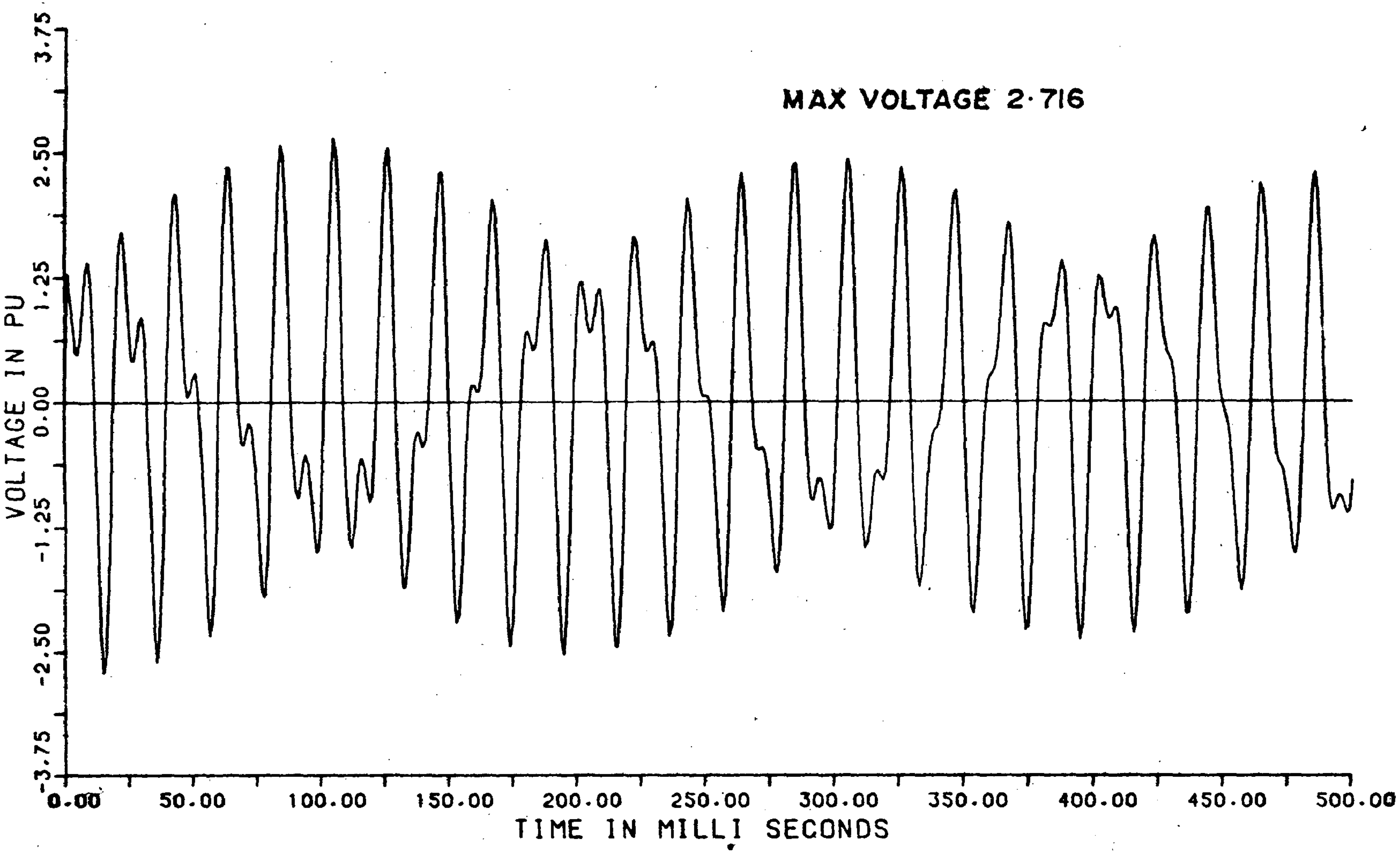


FIG.6·6 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(REACTOR AT BOTH ENDS)

(50 MVAR REACTOR)

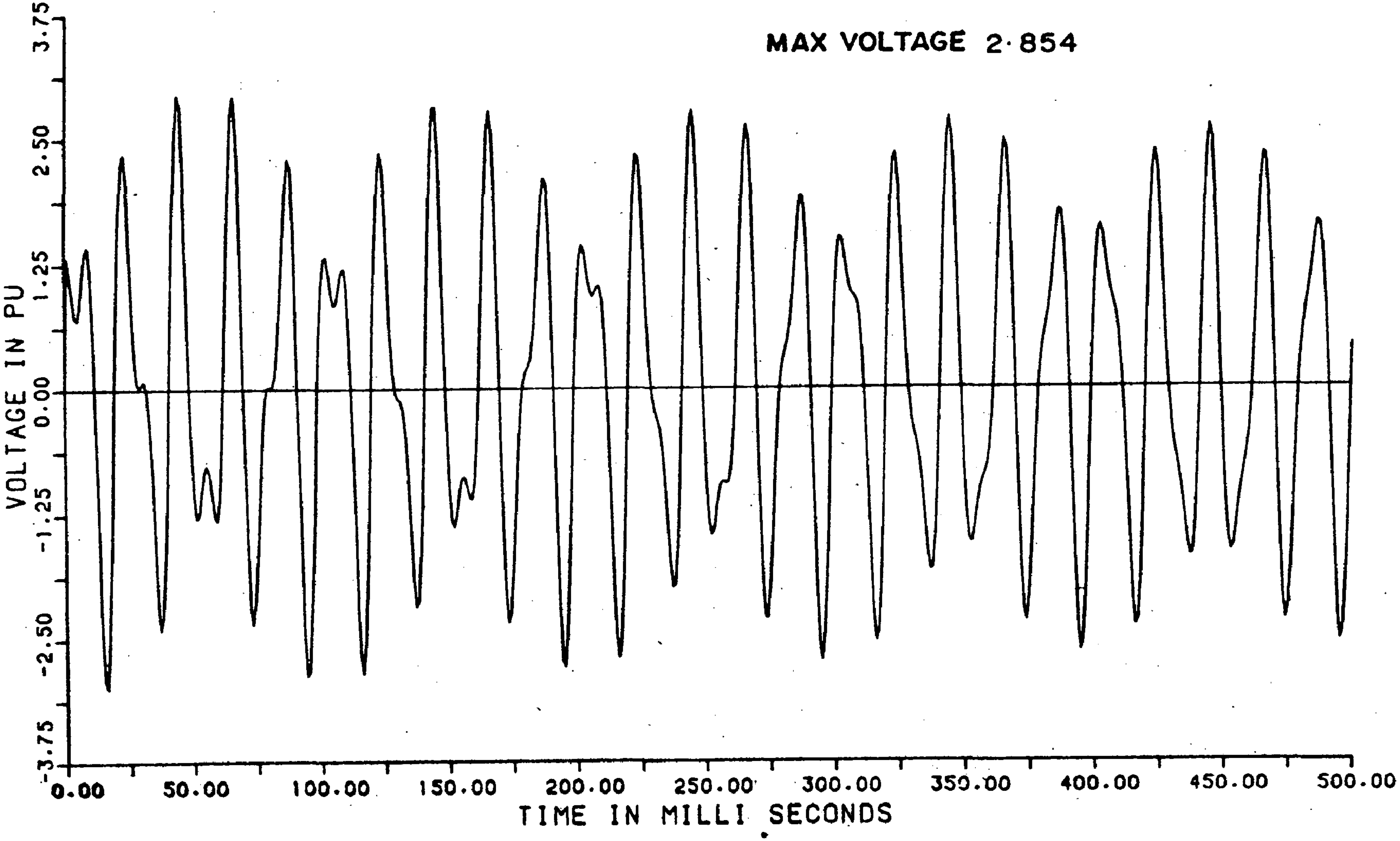


FIG.6·7 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(REACTOR AT SENDING END)

(75 MVAR REACTOR)

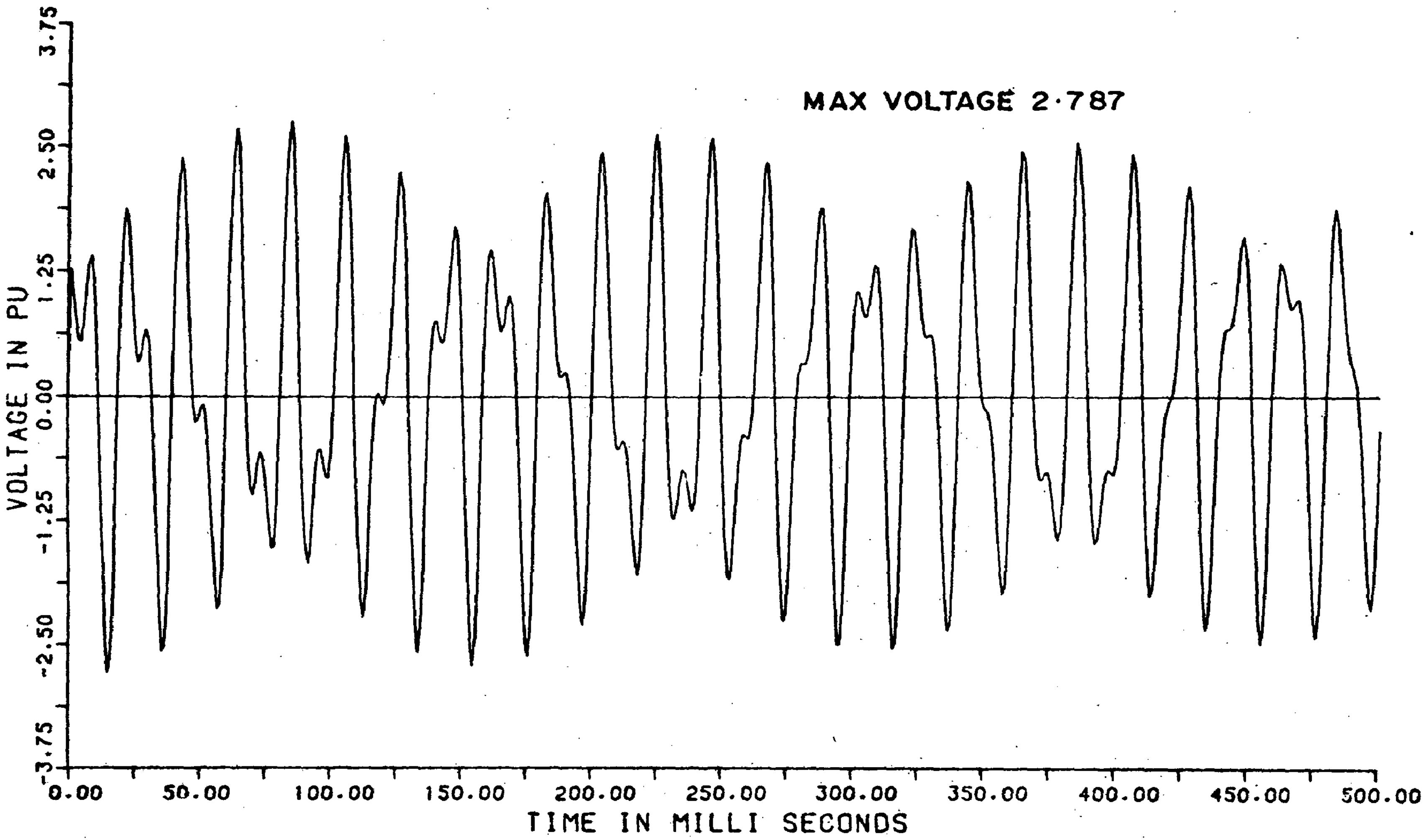


FIG.6·8 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(REACTOR AT RECEIVING END)

(75 MVAR REACTOR)

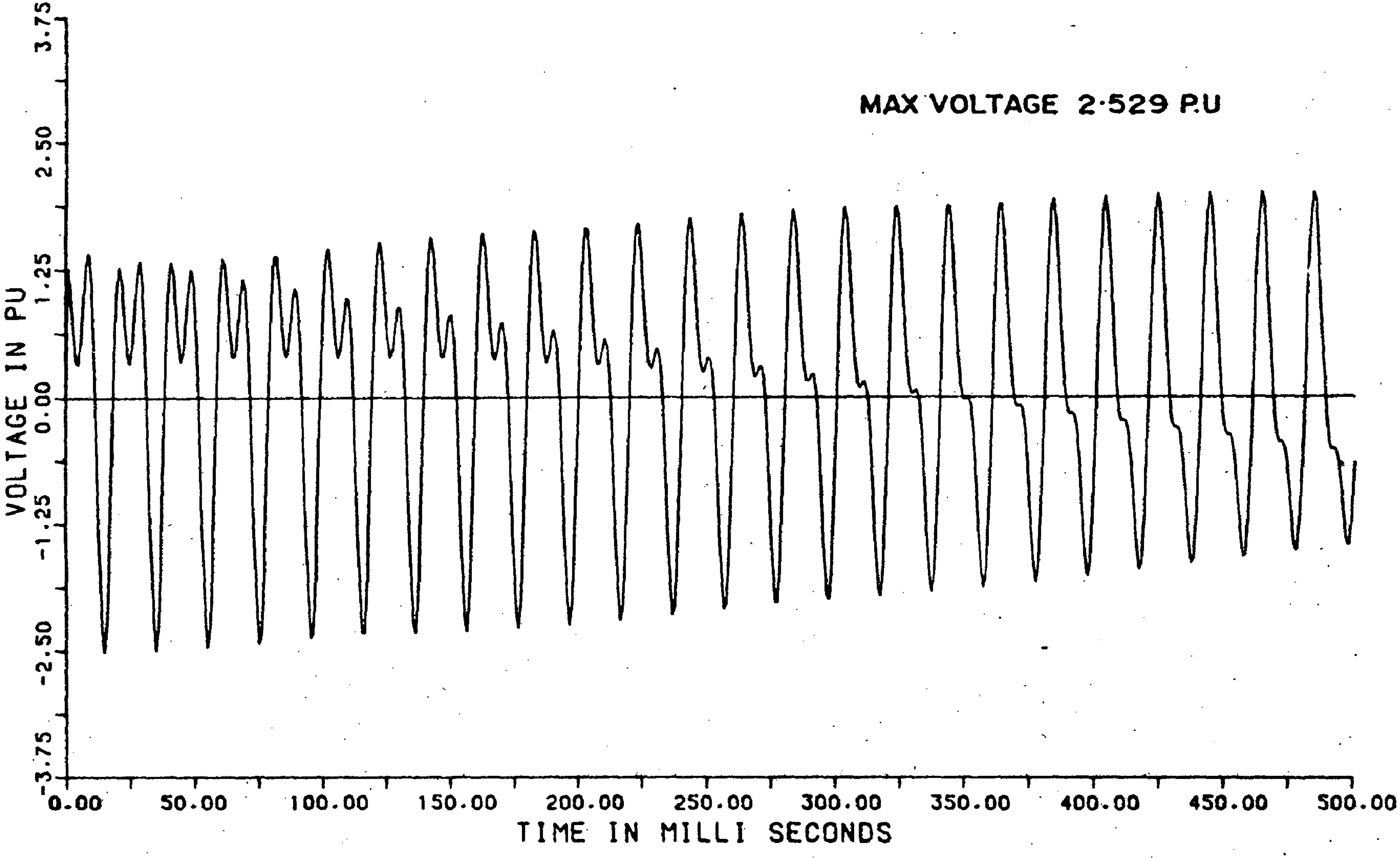


FIG. 6·9 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(REACTOR AT BOTH ENDS)

(75 MVAR REACTOR)

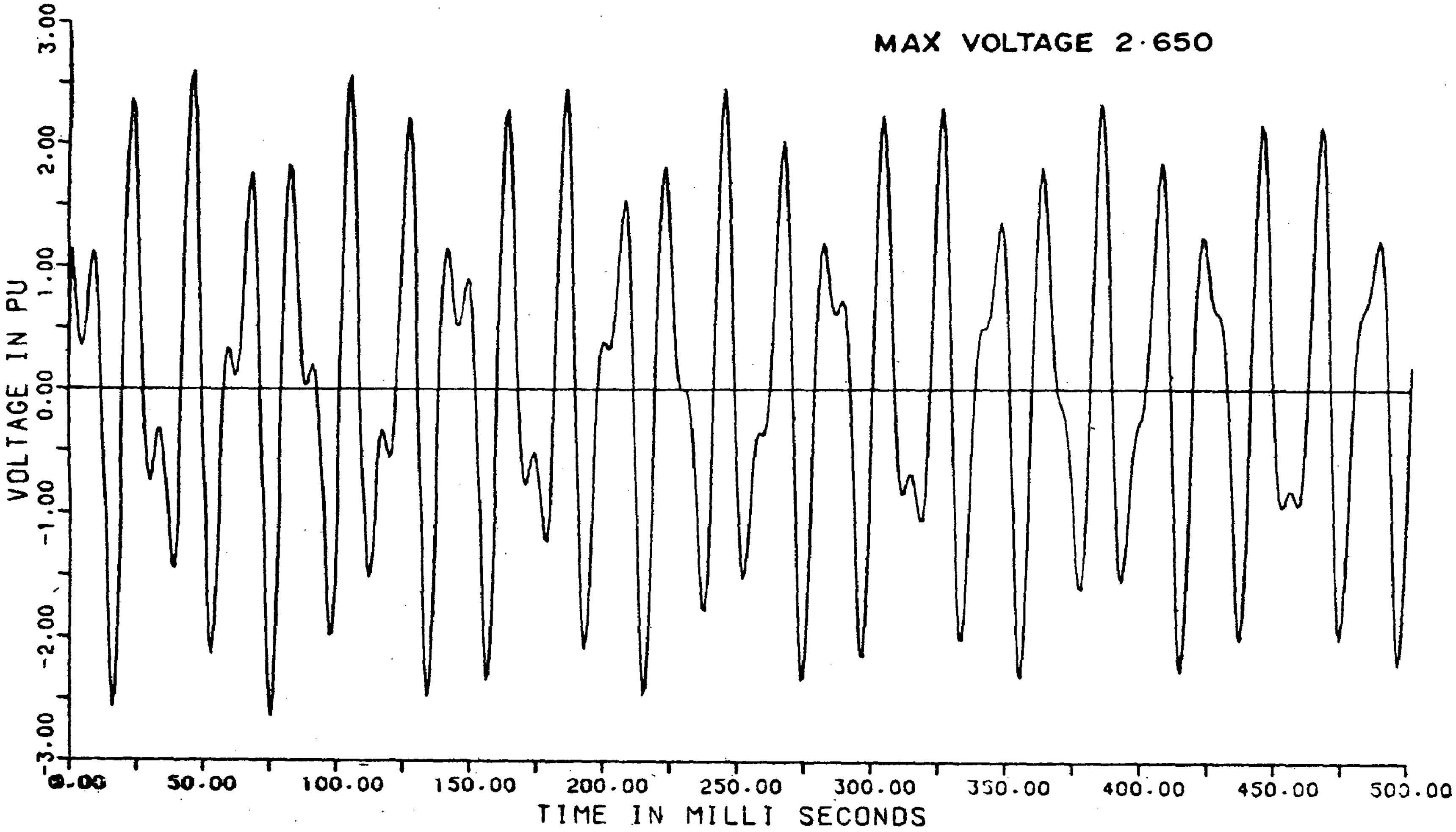


FIG. 6·10 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(WITH REACTOR LOSSES)

(75 MVAR REACTOR)

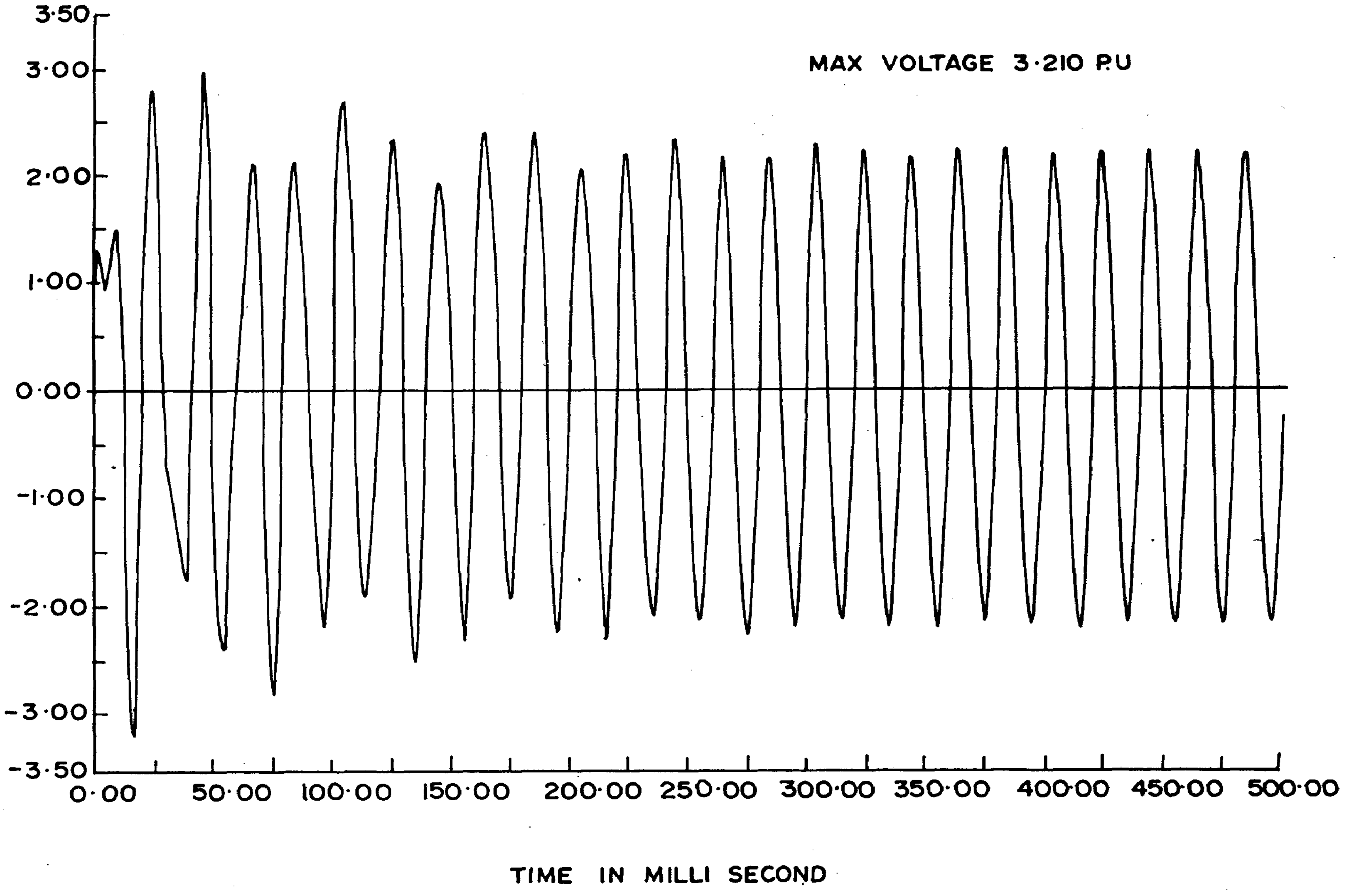


FIG. 6·11 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION (WITH T-LOSSES)

MAX VOLTAGE BEFORE SWITCHING 3·36 P.U
MAX VOLTAGE AFTER SWITCHING 2·94 P.U

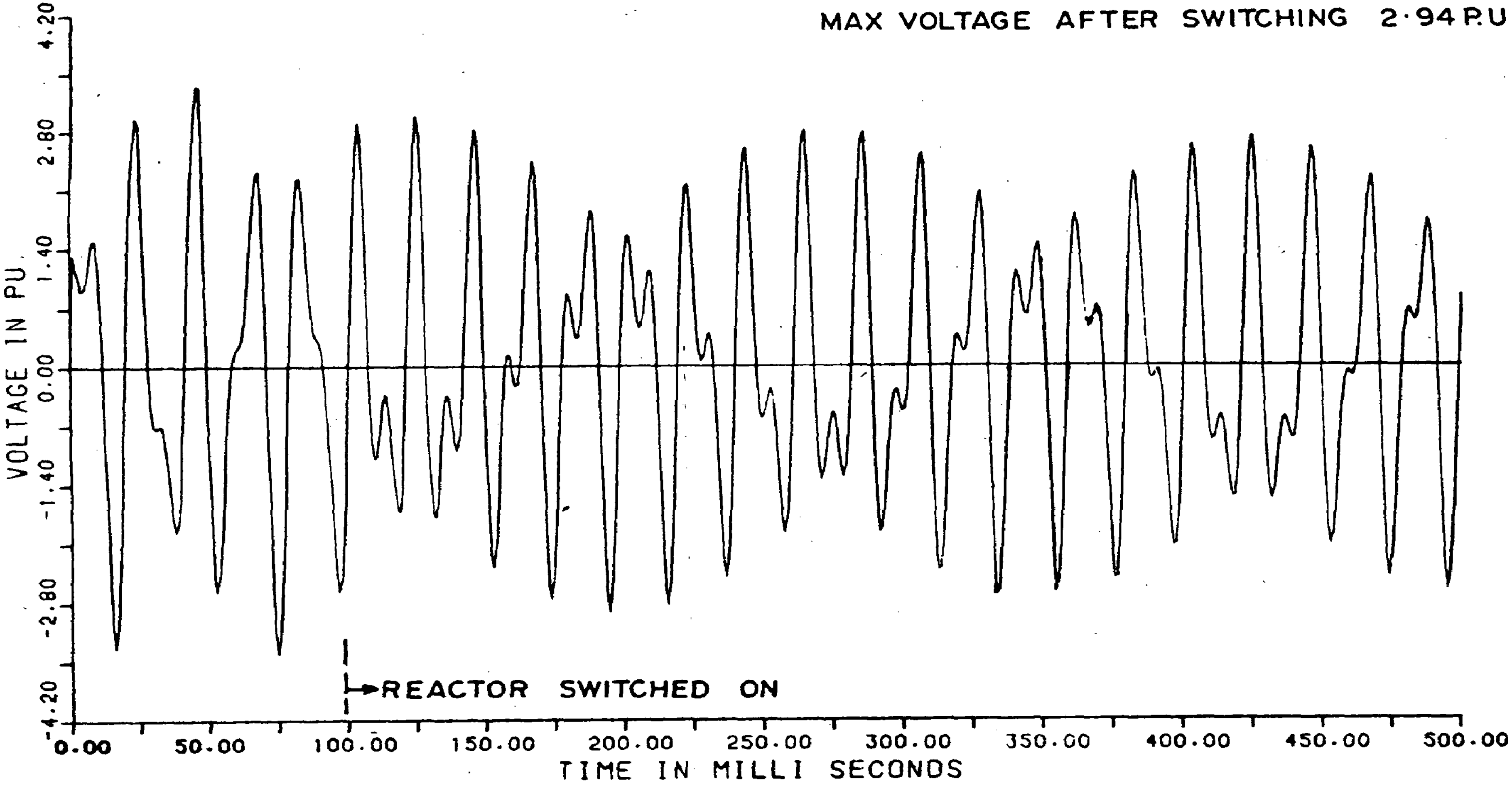


FIG.6·12 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(SWITCHED REACTOR)

(75 MVAR REACTOR)

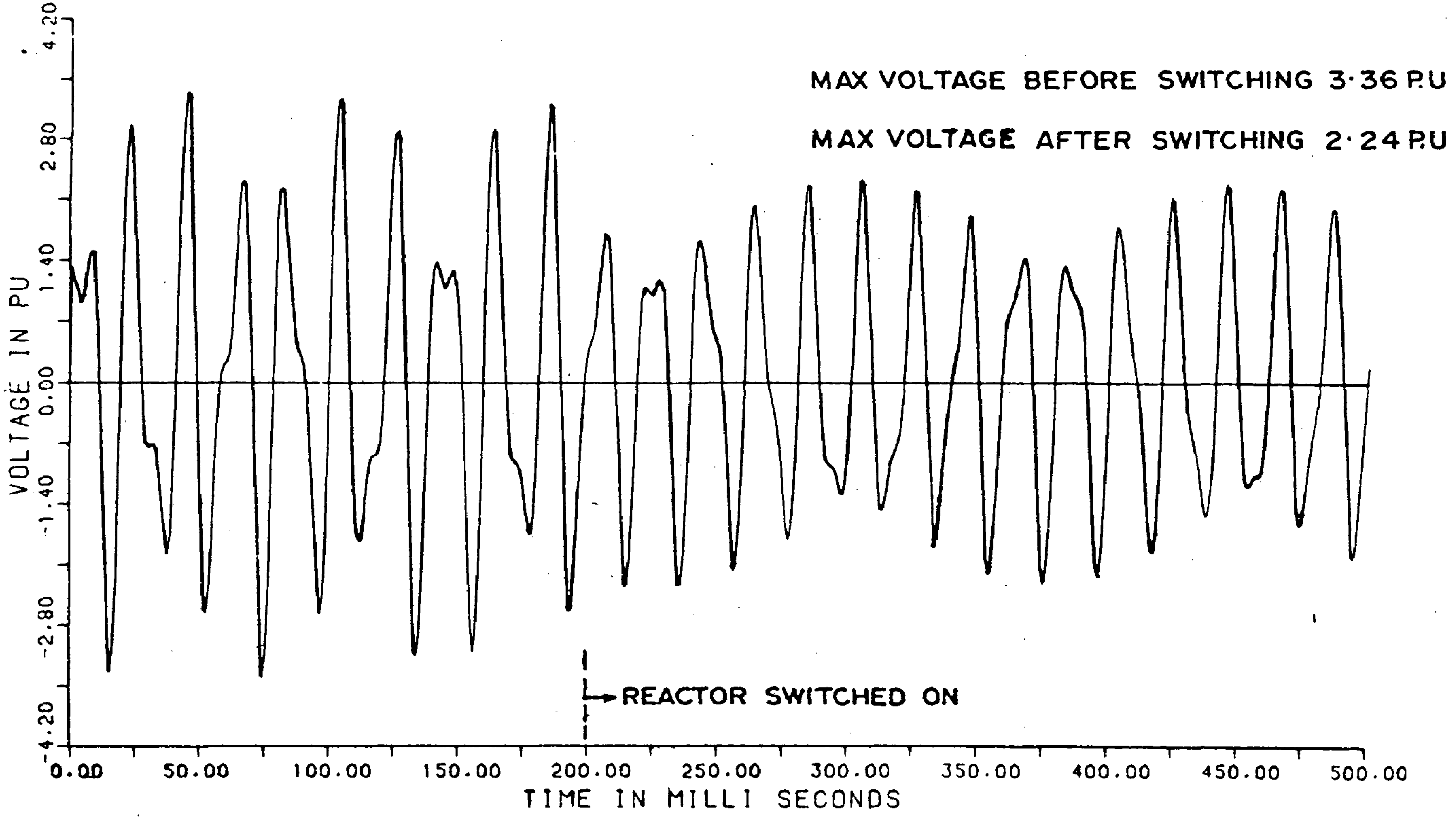


FIG.6·13 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(SWITCHED REACTOR)

(75 MVAR REACTOR)

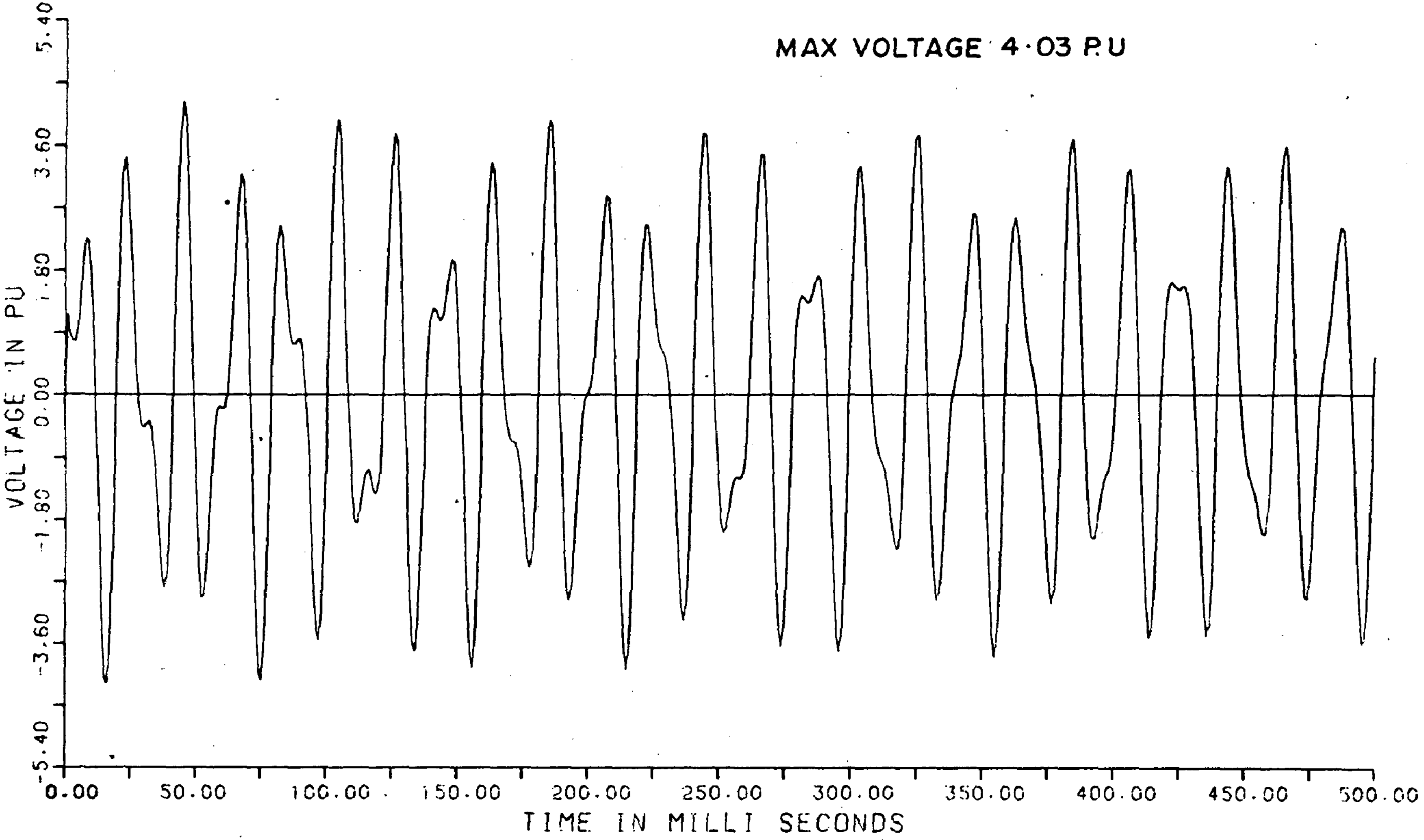


FIG.6·14 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION

(SERIES COMPENSATION)

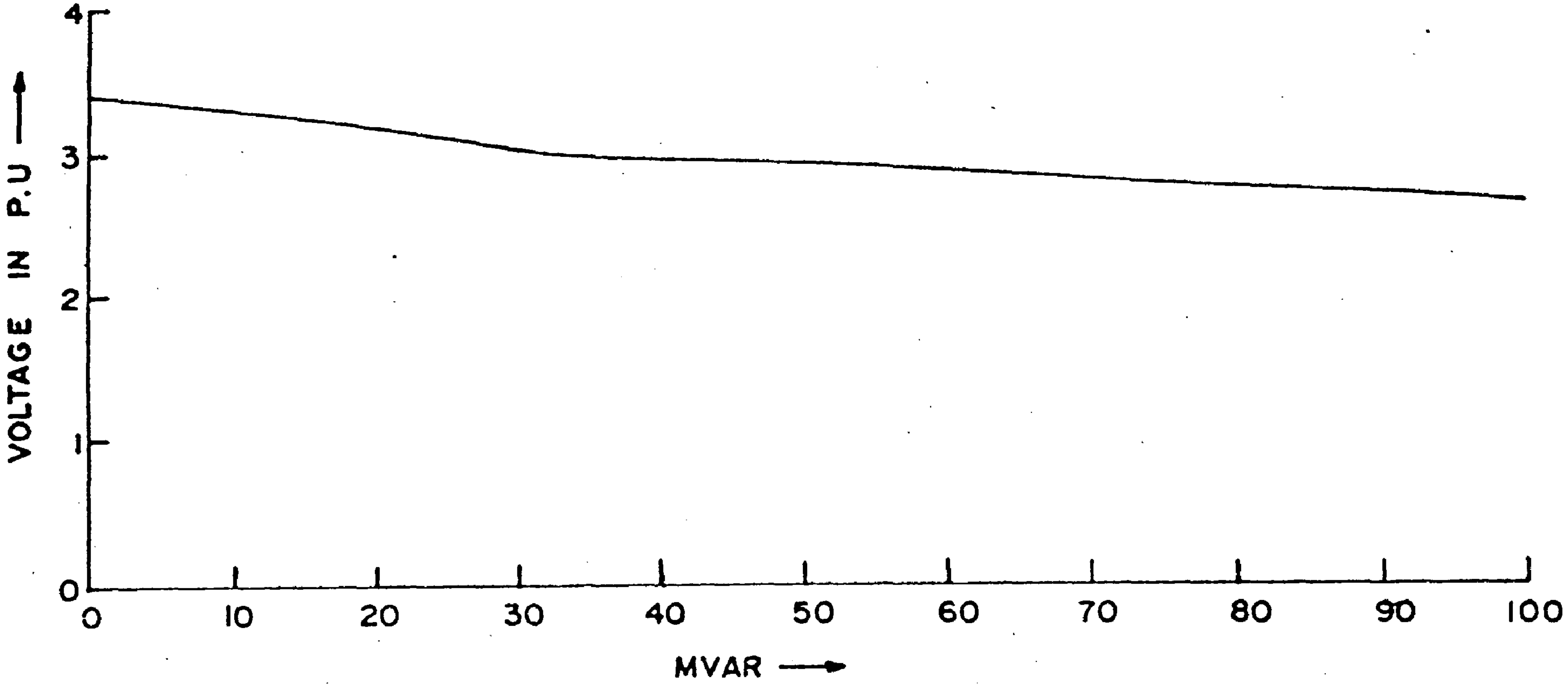


FIG.6·15 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION
(VARIATION OF MVAR VALUES OF REACTOR)

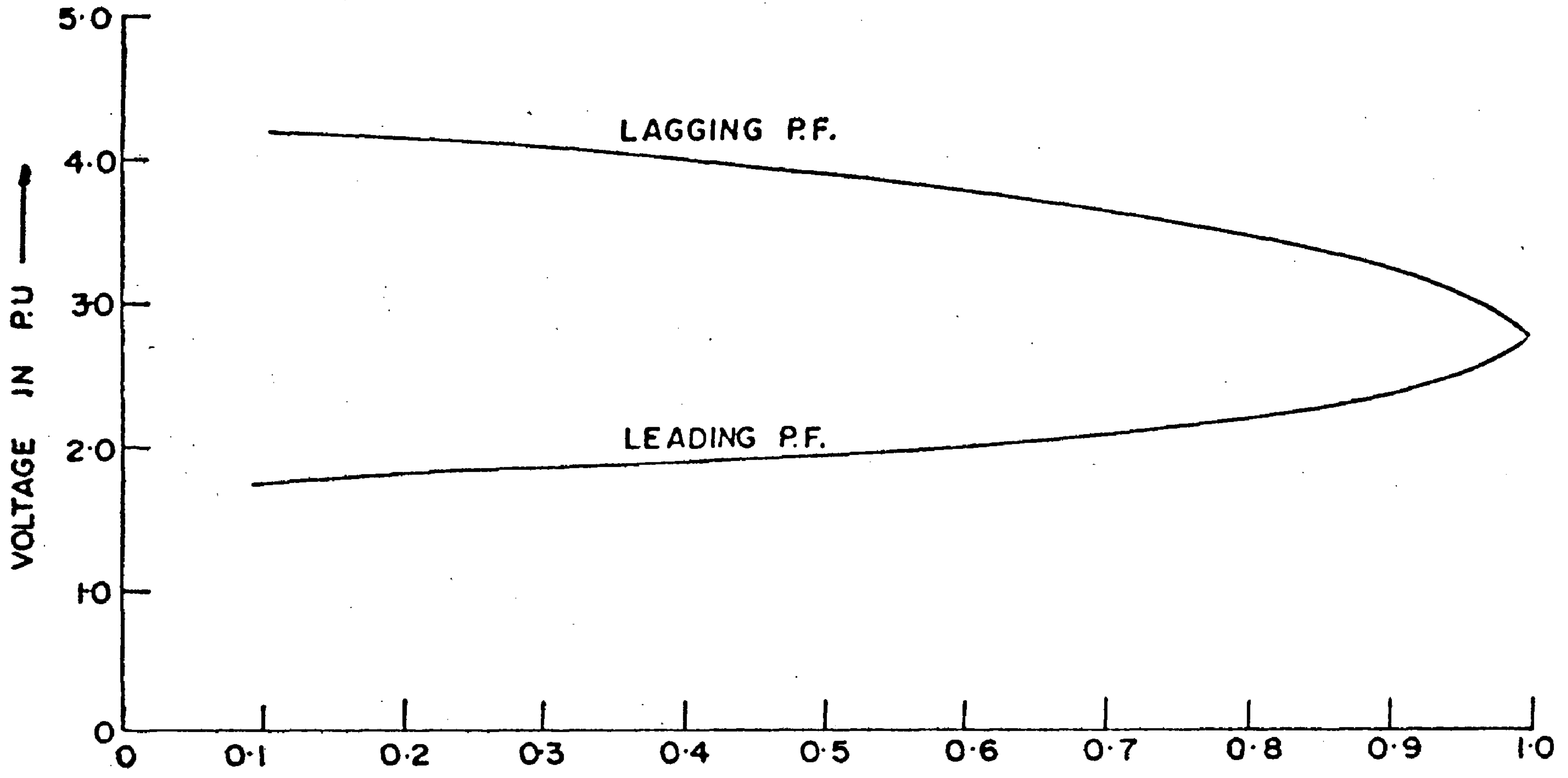


FIG.6·16 DYNAMIC OVERVOLTAGE DUE TO SUDDEN LOAD REJECTION
(VARIATION OF LOAD POWER FACTOR)

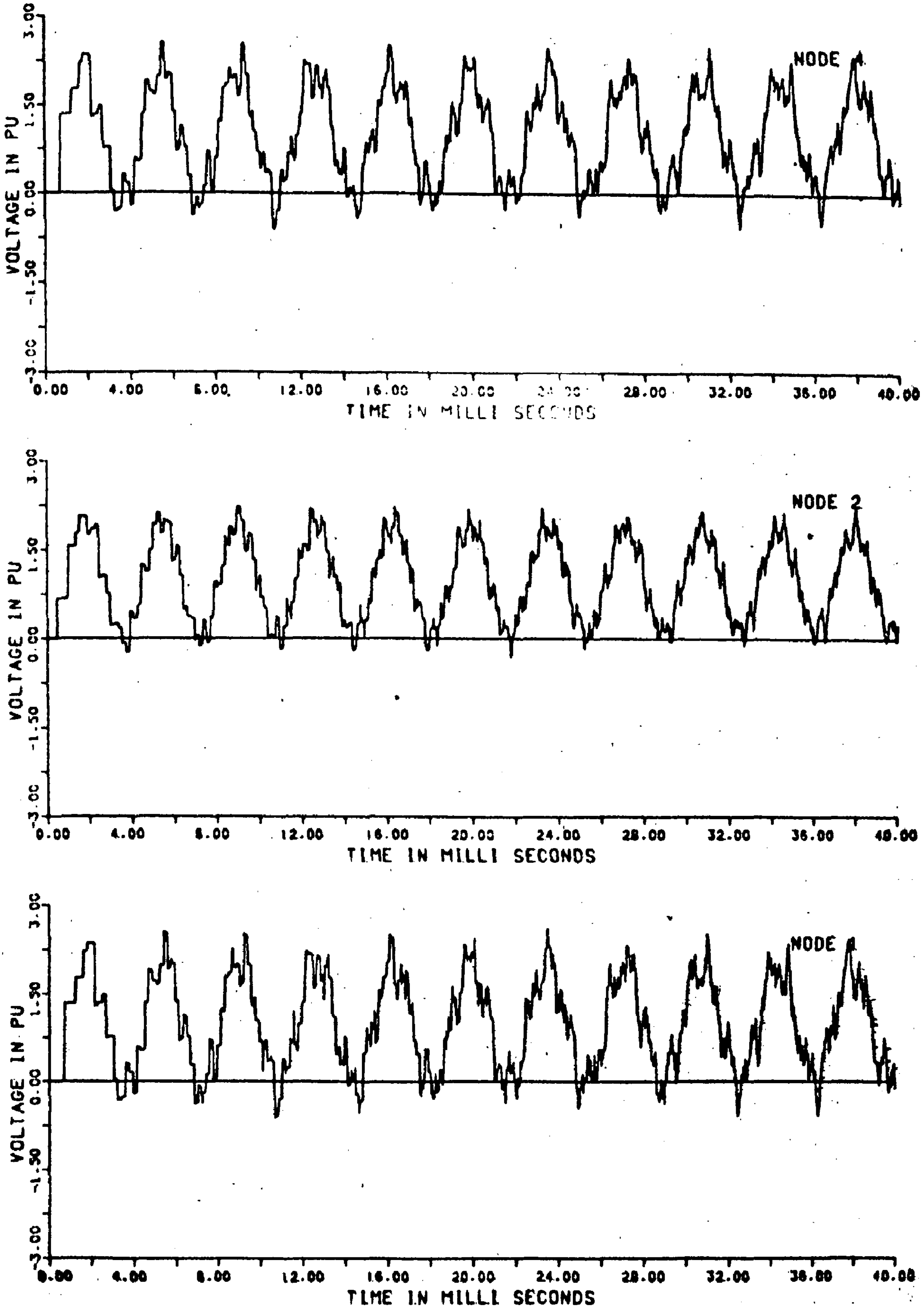


FIG.6.17 SWITCHING OVER VOLTAGE

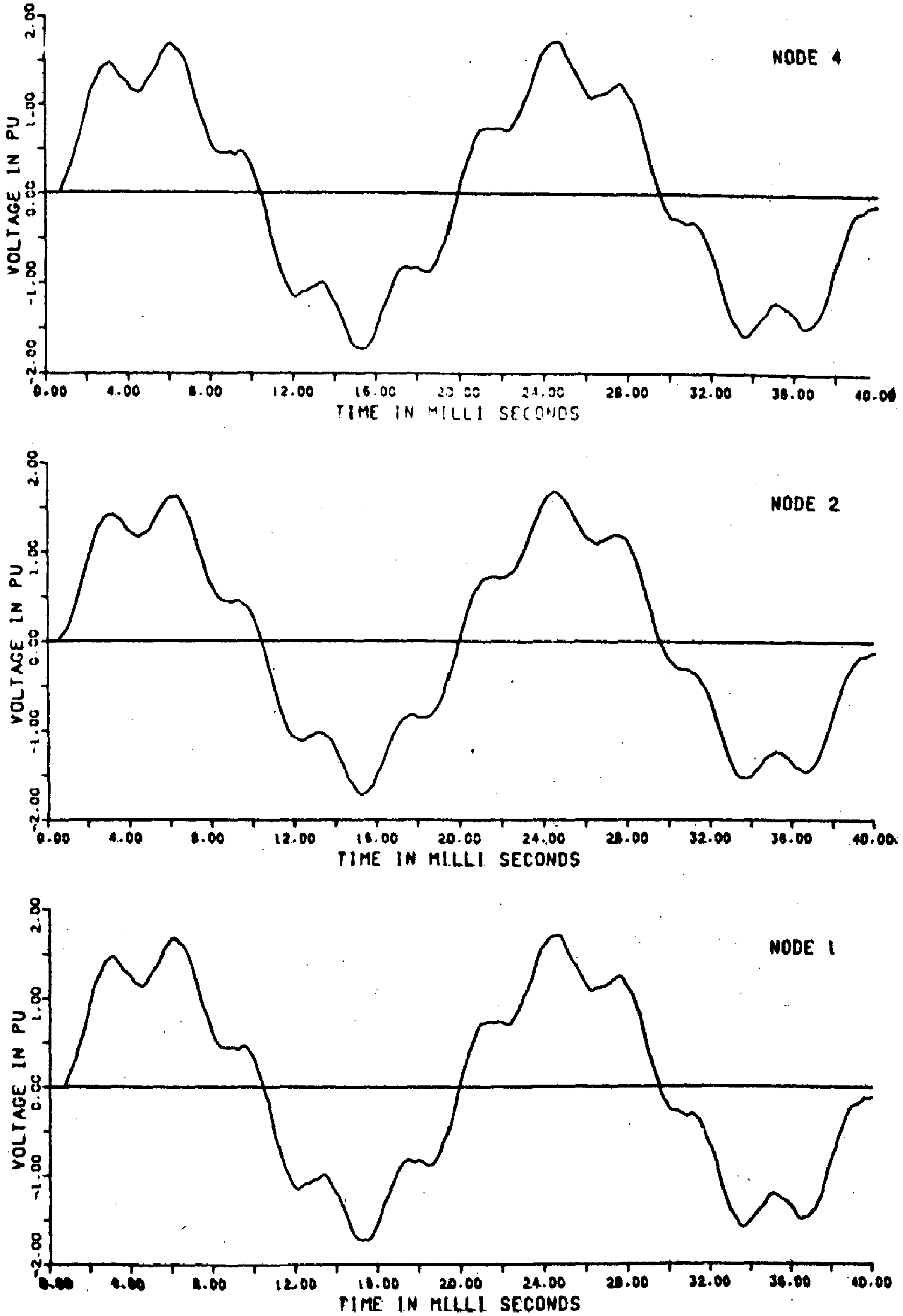


FIG.6.18 SWITCHING OVER VOLTAGE

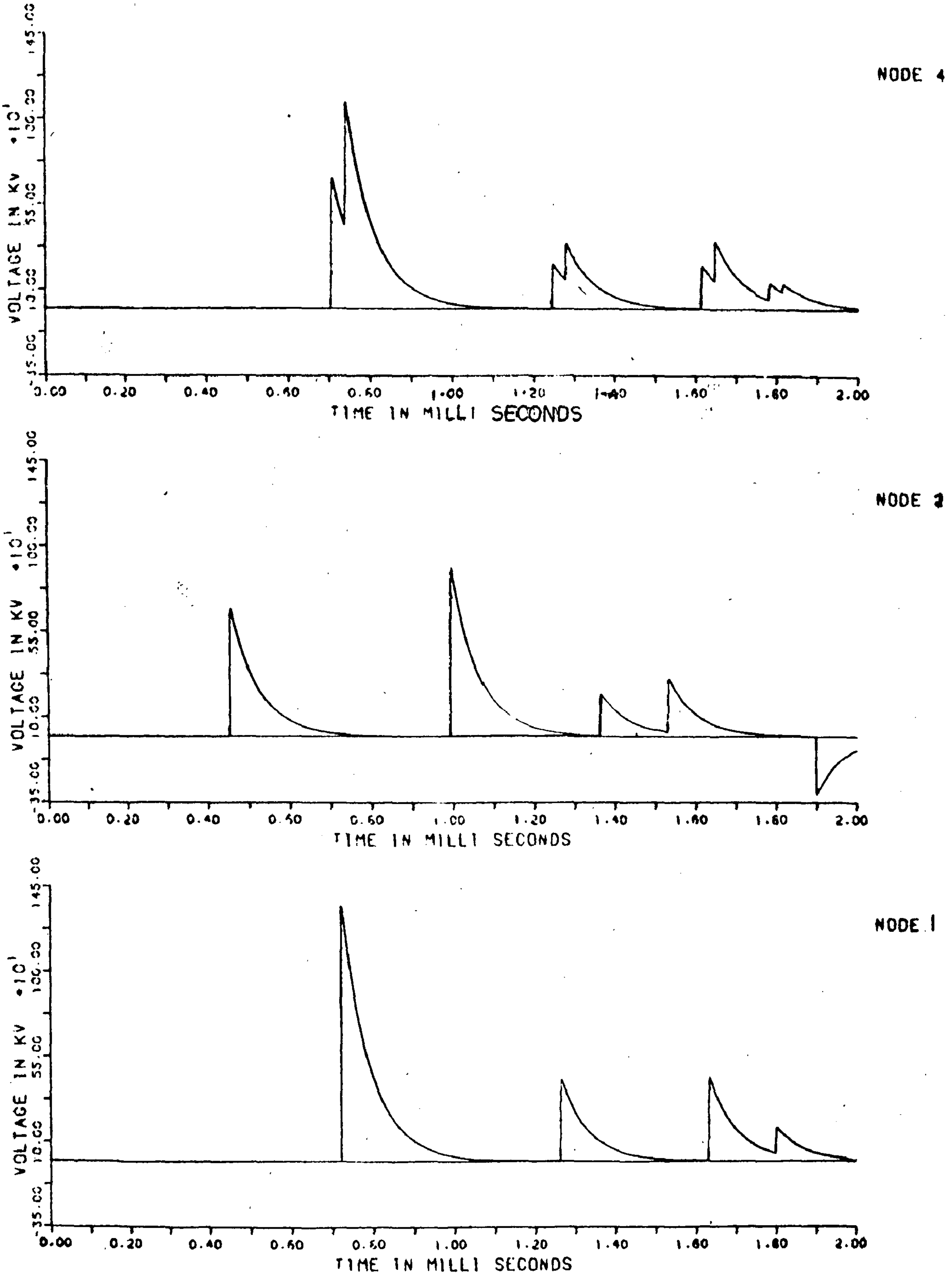


FIG.6.19 LIGHTNING OVER VOLTAGE IN NEPAL 132 KV SYSTEM

Table 6.II

Switching/lightning overvoltages

S.No.	Case	Max. Over-voltage	Ref.Fig. No.
1.	Unit step input	2.19 p.u	6.17
2.	Sinusoidal input	1.15 p.u	6.18
3.	Lightning impulse input	1360 KV	6.19

6.2 DISCUSSION :

For load rejection at receiving-end at power factor 0.85 lagging and receiving-end voltage of 1.0 p.u the magnitude of overvoltages increases with the increase in quantum of load rejected. The maximum overvoltages for load lost of 150 MW, 300MW and 450MW observed to be 3.405p.u, 4.203p.u and 4.962 p.u respectively. The increase in initial peak is attributed to greater initial shock to the system resulting from the rejection of load. This is due to the fact the maximum overvoltage depends on the magnitude of disturbance caused by the amount of load. And also, the transition of fully loaded to no-load condition of the line is accompanied by the necessity of absorbing the reactive power of the line. The range and rate of variation of reactive power demand varies widely on the types and quantum of load.

Shunt reactors are normally used to limit the voltage rise due to the Ferranti effect. When shunt reactors are connected to either end or at both ends, the overvoltages are reduced to a lower value. It is also observed that the location of the reactors on the transmission line has considerable effect on overvoltages, which is affirmed by the results. The reactor situated at receiving-end results in lower voltage (2.783 p.u) than those obtained by providing reactor at sending-end (2.854 p.u). It is because of the fact that, normally as observed, receiving end voltage is higher than the sending-end voltage after the load is rejected and by providing reactor at receiving end better compensation results in lower overvoltages. The magnitude of overvoltage is further reduced by connecting reactors at both the ends (2.529 p.u). This is due to better compensation of line charging MVAR at both the ends.

On connecting a 50MVAR reactor at sending-end, receiving-end or at both the ends the maximum overvoltage turns out to be 2.990 p.u, 2.923 p.u and 2.716p.u respectively. When the MVAR value of this reactor is changed from 50 MVAR to 75 MVAR the maximum overvoltage turns out to be 2.854p.u, 2.783p.u and 2.529p.u respectively. Thus, the magnitude of the over voltages is further reduced with the increase in the MVAR value of the reactor.

When reactor loss is included, the magnitude of overvoltage is reduced and damping is increased. The peak of overvoltage reduces from 2.783 p.u to 2.65 p.u when the reactor losses are considered. This is due to the fact that the losses cause attenuation of the voltage wave on the line owing to an energy loss. In general, their net result is to cause a reduction in the over voltage magnitude at any point on the line.

When transformer loss is included the magnitude of overvoltage is reduced and damping is increased. It is also due to the above mention reasons. Thus, when reactor and transformer losses are neglected higher overvoltages are observed.

Reactors are normally not connected to the line when the load is connected at the receiving end. They are to be switched on to the line just after the load is rejected. It was observed from the results that the instant of switching has a considerable effect on the wave shape. A slight delay in switching results in lower steady state overvoltage. A detailed study in this regard needs to be carried out to determine best instant of switching. Higher magnitude of overvoltage is observed for a series compensated line. It is because series capacitor reduces the inductive reactance between the load and supply point, which increases the charging MVAR of the line resulting in higher overvoltage after the load rejection.

When the MVAR values of receiving-end reactor is varied from 10MVAR to 100 MVAR value considerable reduction in overvoltage is observed upto the value of 70MVAR rating. The reduction in overvoltage is very small after increasing the value of reactor beyond 70 MVAR value. The reduction in overvoltage is about .04 p.u per 10 MVAR increase in reactor value after 70MVAR as compared to about 0.1 p.u per MVAR before 70 MVAR. Hence it may not be economical to provide reactors ~~of~~ with MVAR rating higher than 70 MVAR.

Dynamic overvoltages are quite sensetive to load power factor. They will be, in general greater for lagging power factor. This is because of the fact that as the power factor becomes lower the sending-end voltage required to maintain 1.0 p.u rated voltage at the receiving end increases. This increased sending end voltage results in higher overvoltages after load rejection. With leading power factor loads a lower overvoltage results because lower sending-end voltage will be needed to maintain the rated 1.0 p.u voltage at the receiving-end.

When lightning impulse strike the line steep rise in voltage at different nodes is observed. This is because lightning introduces steep fronted unidirectional voltage wave which usually has a rapid rise to the peak value and slowly falls to zero value. In these studies line losses is neglected, due to this reason also steepness of voltage wave is high.

When step function and sinusoidal voltage wave is applied to the line overvoltages are observed at different nodes. But the voltage peak due to step function is higher than that due to the sinusoidal voltage wave. This is because in the case of step function same magnitude of voltage is constantly applied to the line, where as in the case of sinusoidal wave it varies with time. The overvoltages at different nodes occured at different time, because it depends on the time taken for a wave to travel from one end to another depending upon the length of line.

In these studies line losses are neglected, therefore, the shape of the reflected and transmitted waves are the same as the original wave.

6.3 CONCLUSIONS

The following conclusion can be arrived at from the results.

An uncompensated line is subjected to severe overvoltage when large amount of load is suddenly thrown-off. The voltage rise is greater at receiving-end due to ferranti-effect of the long lines. This effect is more dominant in case of hydro-stations, which are at remote places, connected by long transmission lines to load centres.

State-space techniques of networks analysis provide a convenient and powerful tool for determination of overvoltage in high voltage system. From the study presented here, it may be concluded that the use of reactors generally to reduce the magnitude of dynamic overvoltages. Such reactors may also be needed to control the steady-state voltages which will exist at the load end of the line under light load conditions due to excessive capacitive MVAR supplied by the line. They may also be benificial to control the transient overvoltages on the line. For the system studied the reactor value of 75 MVAR was selected. Even by providing reactors at both the ends the steady state overvoltage level was quite high. To control it further reactor at the mid point of the line may be provided. The other alternative for further reduction could be the control of overvoltage by lightning arresters at the substation.

For overvoltage control of series compensated line the capacitor should be switched out of the line after the load is rejected to reduce leading MVAR consumption of the line.

Although a number of methods may be used to calculate switching transients, at the present time the use of the most accurate method cannot be used due to the system data limitations. Hence, for this study travelling wave method provides some information regarding the relative magnitude of overvoltages expected at various nodes of the line. A single phase representation may be used to determine the relative severity of the overvoltages under different conditions. The accuracy of solution can be further increased by including line losses.

CHAPTER - VII

FUTURE SCOPE OF WORK

An accurate modelling of the system component has a significant influence on the determination of dynamic overvoltage, therefore, an exact analysis of dynamic overvoltage due to sudden load rejection needs detailed generator modelling considering various types of governer and excitation systems.

In the present work the linear reactors have been considered. But in practice the reactor may have non-linear characteristic. Hence for more realistic study the effect the non-lineraty of reactor may be studied.

In switching surge calculations the effect of line losses on attenuation of wave may be studied. The program discribed in this work may be modified to include the attenuation effect due to line resistance and corona losses.

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APPENDIX - I

The computer program developed for the calculation of dynamic overvoltages was written in Fortran-IV. The program consists of main program and two sub-routines. The flow diagram of the program is given in Fig. A.I

MAIN : The main program reads the input data and controls the calling of subroutine INICO and DIFF. It also stores the results for plotting by CALCOM plotter for which a separate program was written.

SUBROUTINE :

INICO : It calculates the initial condition of the system for the given load and power factor. These initial conditions are to be used for the solution of state equation.

DIFF : This solves the differential equations by Runge-Kutta fourth order method.

The program for calculation of switching overvoltage using travelling wave method consists of a main program only, where all the steps of calculations have been implemented. The flowchart of the program is given in fig. A-II.

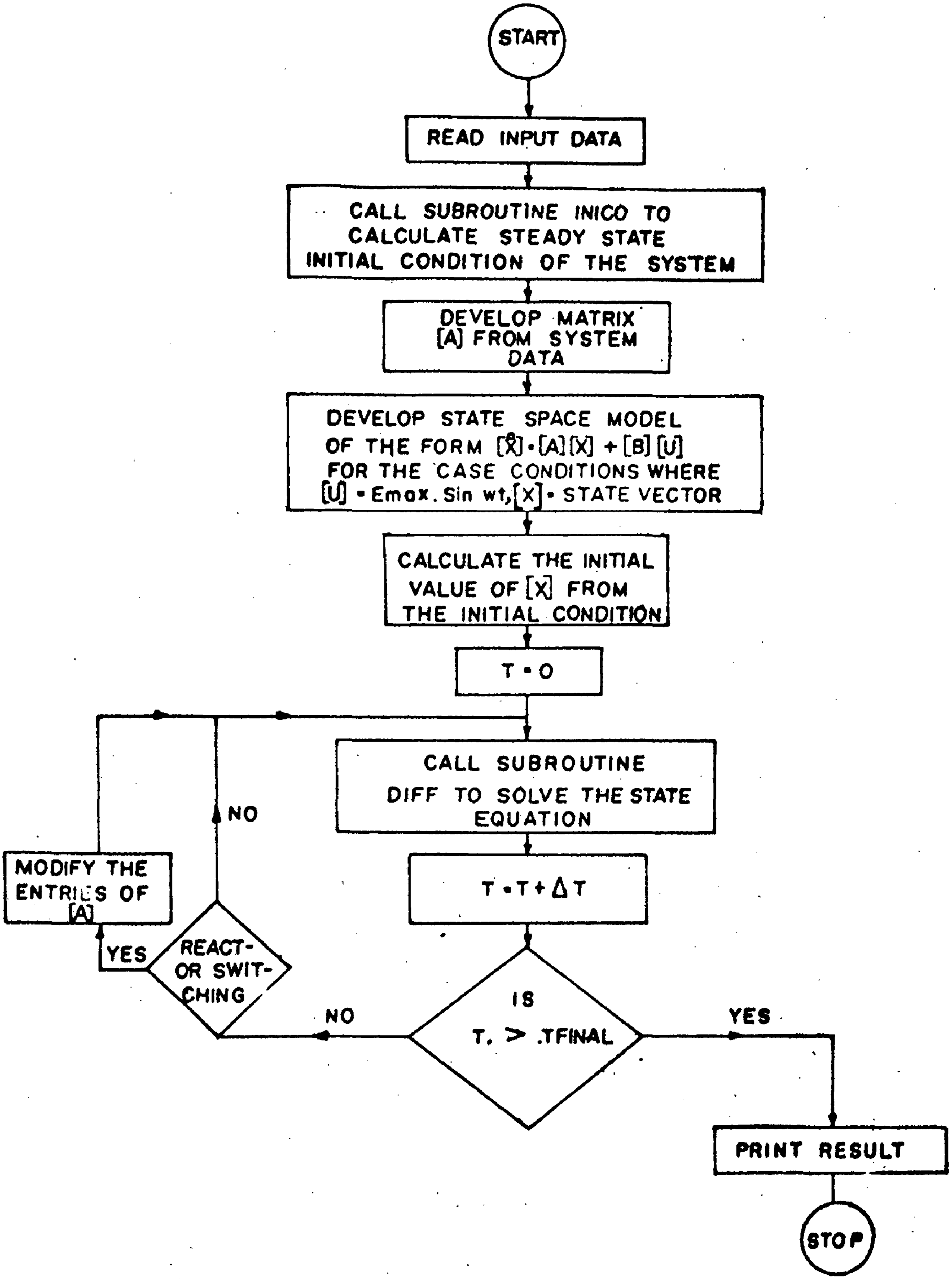

FIG. A-I FLOW DIAGRAM OF DIGITAL METHOD FOR DYNAMIC OVERVOLTAGE ANALYSIS

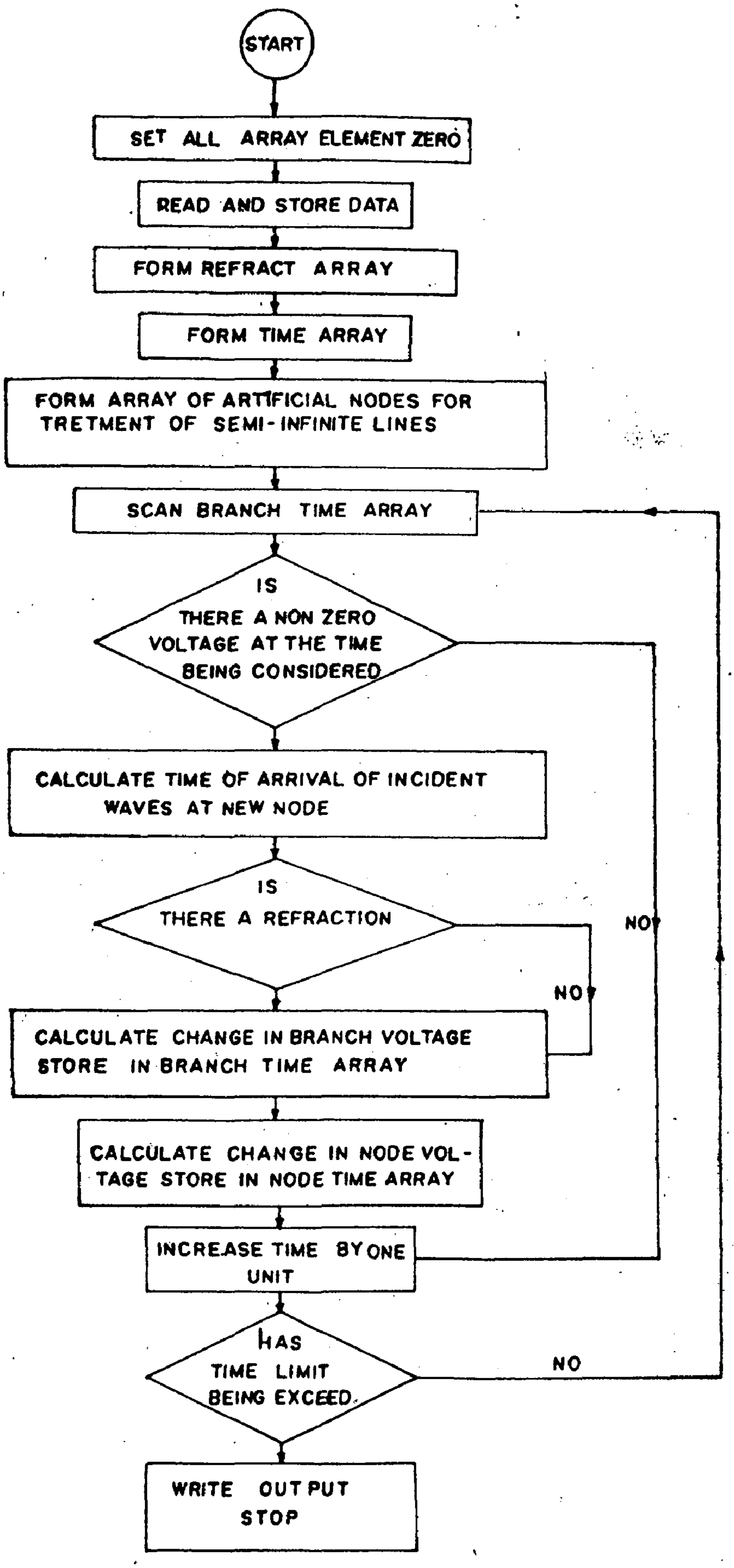

FIG. A-II FLOW DIAGRAM OF DIGITAL METHOD FOR TRAVELLING WAVE ANALYSIS