DESIGN OF A TRANSIENT ANALYZER

AND

STUDY OF TRANSIENT PERFORMANCE OF A POWER SYSTEM

BY

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A THESIS

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CERTIFICATE

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

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SIGNATURE OF THE CANDIDATE.

Accepted as satisfactory for partial fulfilment of the requirements for the award of the degree of Master of Science in Engineering (Electrical).

EXAMINERS:

(1)

(II)

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ABSTRACT

A Transient Analyzer has been designed, built and tested. The design calculations and construction details of the network components are presented. Subsequently the model transient analyzer was utilized for studying voltage and current transients at selected points of an existing power system for simulated fault conditions, switching operations and lightning surges. A sample investigation of resonance phenomena is also presented by initiating pulses of varying repitation rate. The magnitude of switching and lightning surges and their effects on the system performance is also discussed. The studies included comparison of transient voltage magnitudes with protective insulation levels of the system and the apparatus. An alternative approach- the Digital method of transient studies on a system was also investigated. Suggestions for improvement of the existing system are given and future research area is defined.

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CHAPTER - 1

INTRODUCTION

1.1. TRANSIENTS: BASIC CONCEPTS[1]

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. For example, immediately after the establishment of a circuit the currents and voltages have not, in general, settled into their steady state values. The period required for the currents and voltages to adjust themselves to their steady-state modes of variation is called the transient period. The transient periods are usually of short duration and are damped out by certain factors which depend for their values upon the system parameters.

1.2. NATURE OF TRANSIENTS IN A POWER SYSTEM[2]

Internal(switching) transients arise during sudden change in the operating conditions of the system. For example by a switch-in or switch-out or sudden change in load, the occurrence of short circuits and the interruption of short circuit current, the operation of Circuit Breakers(CB) to connect and disconnect equipments and transmission lines.

External (lightning) transients occur as a result of the action of lightning discharge upon electrical installations. These surges may be because of induced charges or direct stroke upon the system.

In all the cases outlined above the circuit condition is changed so that a new distribution of currents and voltages is brought about. This redistribution is accompanied in general by transient periods and transient overvoltages appear because of sudden liberation of a portion of the stored energy of the system. Such transient disturbances nearly always occur throughout the power system giving rise to excessive currents and voltages.

1.3. EFFECTS OF TRANSIENT OVERVOLTAGES ON POWER SYSTEM PERFORMANCE AND IMPORTANCE OF TRANSIENT STUDIES.[3],[4]

The switching surges under different conditions may be 3 to 4 times the normal voltage rating while the lightning surges may exceed by several tens of times the working voltage seriously affecting the system.

So an overvoltage protective device must function on any transient overvoltages (switching or lightning) of sufficient magnitude and limit that voltage to a value lower than the value corresponding to the dielectric strength of the insulation being protected. Other normal switching surges can be controlled by improving the design of the circuit breakers to give a reduction in the restriking transient voltages. Two factors for the proper selection of circuit breakers are the transient over current flowing immediately after the occurrance of faults and the current which the breakers interupt after 2 or 3 cycles later. These currents also serve to determine the required setting times for the different relays of the system.

It is therefore of vital importance to know what these system transient over voltages and currents are in magnitude and duration for the design of an effective protective relaying system for increased reliablity of system operation, selection of proper rating of circuit breakers and ascertaining the corresponding insulation protective level at different parts of the system. These in turn are also important in determining the allowable apparatus insulation levels, that is making possible a reduction in insulation, particularly that of large power transformers, to obtain reduced system costs without sacrifice of reliability.

Thus although in the early years of electrical engineering, power system were designed according to the requirements of regular sustained operation, experience showed that with switching processes and lightning discharges peculiar phenomena appeared which greatly disturbs the regular operation of the system.

Hence in the design and the operation of electric systems, the transient phenomenon has assumed, in general, the same significance as the regular performance in the steady state.

Moreover, some of the transient phenomena, like short circuits in a network, instability of the synchronous generators and lightning disturbances on transmission lines, have become of such outstanding importance that the layout of modern power systems is predominantly determined by these conditions.

A thorough and useful study of the transient performance of Bangladesh Power Systems have not been undertaken sofar, although stability studies have been done occasionally.

The object of this work is to design , and build a Transient Analyzer and to study the transient performance of the existing system for improving its overall performance.

1.4. LITERATURE SURVEY

1.4.1. BACKGROUND:

In the early years of electrical engineering, power systems were designed according to the requirements of regular sustained operation. However, with the passage of time, experience showed that with switching processes in the circuits and during lightning discharges and under similar other intensional or accidental conditions peculiar phenomena appeared which could greatly disturb the regular operation of the system.

Numerous investigations were endeavoured to clarify scientifically these phenomenon and new tools were developed and put to use in studying many of the circuit transient phenomena previously avoided simply because of the prohibitive amount of time required for arriving at the desired understanding with the means then available. This has resulted in the publication of much technical literature in the course of recent years. Some of the relevant works of interest in this connection, are described below.

1.4.2. 'Transient Recovery Voltages on Power Systems, Part -1- Analysis and Tests of the Ontario Hydro System' By Dandeno, P.L ; Wattson, W and Dillard, J.K.(5)

This paper published in 1958 describes the different methods of determining the transient recovery voltages at a point on a system. The transient recovery characteristics of 230 KV air-blast circuit breakers and 115 KV compressed air breakers of the Ontario Hydro System were studied by an ANACOM representation with an emphasis of the effect of system parameter on recovery characteristics.

A method has been shown by which the conditions of recovery voltage on the Ontario Hydro 230 KV system can be determined.

The results have been presented in as simple a manner as possible, consistent with conveying the maximum amount of information. These, and similar data on the transient recovery voltage of present and future systems, provided a basis for selecting the requirements to which the power circuit breakers should be designed and tested.

1.4.3. "Transient Recovery Voltages on Power Systems, Part II-Practical Methods of Determination" by Griscom, S.B; Santon, D.M. and Ellis, H.M.[6]

This paper published in 1958 classifies the types of circuit breakers transient recovery voltage problems into seven main types or cases. These are further broken down into sub-cases when this is necessary to handle the range of parameters. Methods of approximate solutions to examine quickly circuit breakers recovery voltage situations have been presented.

1.4.4. "Switching Surges on Energizing a Transformer- Terminated Line." by Jonson, I.B; and Schultz, A.J.[7]

The paper published in 1960 describes the results of the study made on a power system in miniature on a Transient Network Analyzer. This study covers the energization of open-ended high-voltage(HV) transmission lines and of lines terminated in transformers. This study reveals the existence of transient energization voltages sufficient to cause operation of modern lightning arresters.

1.4.5. "Surge Potentials on Underground Cable Sheath and Joint Insulation". by Watson, W; and Erven, C.C.[8].

This paper published in 1963 deals with stresses on underground cable sheath due to transient conditions imposed by switching surges, grounding operations, and faults. Field measurements and investigations are done with transient voltages on sheath insulation. On the basis of this study, it is concluded that insulated sheath coatings and sheath-joint insulators are punctured in service, apparently by transient voltages. It has been shown that the discontinuities caused by sheath cross-bonding result in 15% of an applied surge on a conductor, appearing on the sheath at a joint and 30% across the sheath insulator. Bonding transformers result in higher transients. Protective devices appear to be required at each joint. These may be lightning arresters or surge capacitors.

1.4.6. "Field Measurement of Switching Surges on Unterminated 345 KV Transmission Lines", by Mcelroy, A.J. & Others[9].

In this paper published in 1963, field measurements are presented for switching surge, line to ground voltages at both bus and receiving ends of unterminated 345 KV transmission lines of intermediate length, when energizing and reenergizing. Varied and representative configurations were studied. Effects of source configuration and breaker pole closing sequence and pre-striking are demonstrated. An estimate of overvoltage probability is attempted as well as rationalized description of waveforms. Comparison tests on 138 KV lines were also conducted.

1.4.7. "Field Measurements of 345 KV Lightning Arrester Switching Surge Performance", by Mcleroy, A.J.and others[10].

This paper published in 1963 presents the lightning arrester switching surge voltages and currents, measured during a field test programme on a 345 KV system. Surges were produced by energization of a transformer terminated line and by ultra high speed reenergization (UHSR) of arrester terminated lines. Arrester Spark over levels are 1.1 to 1.7 per unit of arrester rating and arrester follow-current peaks were 135 to 940 Amperes. This paper also shows that reduction in insulation, particularly that of large transformers, to obtain reduced system costs without sacrifice of reliability has been made possible because of the improvement in the protective characteristics of lightning arresters.

1.4.8. "A Switching Surge Transient Recording Device". by Perry, D.E. and Others(11).

This paper published in 1968 describes in detail how a switching surge transient recording device has been designed, built and tested. It served as a continuous, unattended monitor of power system switching transients. Rather than reproduce the transient waveform, the recorder senses and records the positive and negative peak magnitudes of the transient to within 4.0 per unit overvoltage limit, the maximum positive and negative rates of rise of voltage within the limits of 20 to 2000 micro second front-time, and the instantaneous voltage level at the time of transient occurrence. The basic operation of the recorder is described and a portion of the data obtained during laboratory and field tests is represented.

1.4.9. "Determination of Transient Recovery Voltages by Means of Transient Network Analyzers". by Colombo, A and others(12)

This paper published in 1968 describes the results of a statistical study of recovery voltage transients in large HV (245 KV) networks using five Transient Network Analyzers (TNA) in different countries. Some TNAs operated at system frequency (50 Hz or 60 Hz) whereas others used higher frequencies (480 Hz) allowing economics in the reactive components. The other main difference was in the method of simulating interruption and representing the system components. The results obtained by the five TNAs were not consistent and the causes of the discrepancies were investigated.

1.4.10. "Digital Computer Solution of Electromagnetic Transients in Single and Multiphase-Networks", by Dommel W.H.(13).

This paper published in 1969 describes a general solution method for finding the time response of electromagnetic transients in arbitrary Single- or multi-phase networks with lumped and distributed parameters. A computer programme using nodal admittance matrix method has been used at the Bonneville Power Administration (BPA) and the Munich Institute of Technology, Germany, for analyzing transients in power systems and electronic circuits. Among important and useful features of this programmes are the inclusion of non-linearities, any number of switching during the transient in accordance with specified switching criteria, start from any non-zero initial condition and great flexibility in specifying voltage and current excitations of various wave forms".

1.4.11 Switching Surges on Northern's States Power Company's 345 KV Circuits' - by Alexender, G.W; Mielke, J.E.; and Trojon, H.T.(14).

This paper published in 1969 reports the results of field tests conducted on the Northern States Power Company's 345-KV transmission system which investigated the effects of various system switching operations on transient over voltages. Following the field tests a transient network analyzer was used to duplicate the field tests and then explore the maximum switching transients which system parameters could produce.

1.4.12 "Co-ordinated Use of Transient Analyzer and Digital Computer for Switching-Surge Studies: Transient Equivalent of a Complex Network". by Clerici, A. and Margio, L.[15]

On the basis of transient network analyzer (TNA) and digital computer tests, this paper published in 1970, discusses the possible correct evaluation of switching over voltages by means of a co-ordinated use of analogue and digital methods, taking into account both frequency and voltage-dependent parameters. Special emphasis is placed on the transient equivalence of a complex network, its digital computation, and its representation on the TNA. Attention is focussed on the range of frequencies involved in the transients following closing operations of lines of intermediate or long length.

1.4.13. "Estimating the Switching-Surge Performance of Transmission Lines," by Hileman, A.R. & Others.[16]

This paper published in 1970 describes the results of an ANACOM Study to investigate the frequency function of the occurrence of a switching surge. A simplified method to estimate the switching surge flash over probability of a transmission line is developed and presented in a series of curves for a 550 KV system.

1.4.14. "Influence of Shunt Reactors on Switching Surges", by Clerici, A.D. and Others.[17]

On the basis of transient network analyzer studies this paper published in 1970 discusses the influence of EHV Shunt reactors on the overvoltages occuring during breaker operations on transmission systems. The comparative importance of line losses and reactor losses on the decay of the trapped charge voltages that oscillate with frequencies dictated by line capacitances and shunt reactor inductances is analyzed. Emphasis is placed on the influence on these oscillations of differant types of faults and line asymmetries. The overvoltages following closing and reclosing operations on different EHV systems with and without shunt compensation are also analyzed; detailed investigation on two 500 KV lines allowed to draw some conclusions about the effect of shunt reactors in reducing both maximized overvoltages and their cumulative frequency distribution and the influence of shunt compensation on optimization of pre-insulation resistors. Some possible means reducing reclosing surges on shunt compensated lines are also presented.

1.4.15 "Dynamic Overvoltages and Ferro-resonance Found in Switching Surge Studies for Iran 400 KV System", by Clarici, A. and Didricksen, Jr. C.H.(18)

This paper published in 1972 describes the most significant results of a study performed for the 400KV Reja Shah Kabir (RSK) hydro electric project in Iran. Emphasis is placed on dynamic overvoltages and ferro resonance caused by saturation of the generator transformer. The effect of changes in generator and transformer reactances on ferro resonance is presented and discussed closing, reclosing and fault clearing over-voltages together with the transients following load rejection are described. The possibility of using single phase reclosing is also discussed.

1.4.16 "Overvoltages on a Series-Compensated 750 KV System for the 10,000 MW ITAIPU Project, Brazil", by Thanssoulis,P (19)

This paper published in 1975 summarizes the most significant results of a transient network analyzer study performed for the ITAIPU transmission system in Brazil. This study considers an installed capacity for 10,000 MW to be transmitted over 900 KM from the Itaipu Power Plant to the Sao Paulo load area. Fault initiation, fault clearing, energization and reclosing overvoltages on two possible 750 KV a.c. schemes are mainly described. Emphasis is placed on some special transients which can be associated with seris-compensated schemes and which can be of importance to insulation co-ordination, reclosing and equipment specification. Methods for controlling these transients are also proposed.

1.5. SCOPE OF THE THESIS

The scope of this thesis lies in the design of a Transient Analyzer for representing the Eastern Grid Network of Bangladesh Power System and Study of the transient performance of this system.

In order to achieve the above objectives the necessary studies and experimental works were as follows:

(I) To investigate the causes, nature and effect of transients on the design and performance of a power system.

(II) To make a comparative study of the methods of transient studies- the Transient Analyzer and the Digital Computer.

(III) To determine the parameter values of the lines at a suitable new base from their per unit values of an existing power system of Bangladesh- The Eastern Grid Network.

(IV) To design the different components of the analyzer and representation of the system on the analyzer.

(V) To study switching surges for different types of loads using the analyzer.

(VI) To study transient voltages and currents during short circuit conditions with the analyzer.

(VII) To simulate and study lightning surges and investigate for possible resonance phenomena at high frequency.

(VIII) To evaluate from the experimental results the overall performance of the system during switching and lightning surges.

CHAPTER - 2

METHODS AND TOOLS FOR TRANSIENT STUDIES

2.1. BACKGROUND: (20)

The planning, design and operation of power systems require continuous and comprehensive analysis to evaluate existing system performance and to ascertain the effectiveness of alternative plans for ensuring continuous reliability and future expansion.

The computational task of determining power flows, voltage and currents resulting from a single operating condition for even a small network is all but insurmountable if performed by manual methods. The need for computational aids in power system engineering led in 1929 to the design of a special purpose analog computer called an a.c. Network Analyzer. This device made possible, with relative ease and precision, the study of a greater variety of system operating conditions for both present and future system designs.

2.2. TRANSIENT ANALYZER STUDIES:

Since 1939 the special A.C. Network Analyzer (called the Transient Analyzer) was used to study the transient behaviour of a power system during a disturbance resulting from fault conditions, switching operations and lightning surges.

The Transient Analyzer consists simply of reproducing in miniature the actual system to be studied. In this miniature system faults of various kinds can be applied, switching can be done for load variation and for simulation of lightning surge. Results can be obtained quickly and making physical observation possible on oscilloscope screen. Permanent records can be obtained by photographic means.

Because of its simplicity and directness, these Analyzers. were found exceptionally useful in studying the behaviour of large complex power systems. By the middle of 1950s as many as 50 Analyzers were in operation in U.S.A. and CANADA and were indispensible tools for power system works.

2.3. DIGITAL COMPUTER STUDIES:[20]

The availability of the large scale digital computers in the middle of 1950s provided equipment of sufficient capacity and speed to meet the requirements of major power systems, for transient studies. Since 1957 in U.S.A. the I.B.M. 704 Digital Computers are used instead of Analyzers in increasing numbers for load flow studies, fault calculations, stability and transient studies.

For transient studies a load flow program is made first to obtain system conditions prior to disturbance. In transient analysis an iterative solution of the algebric equations (load flow) describing the Network is combined with the numerical solutions of the differential equations describing machines behaviour.

The system operations programme modifies the system data at specified time during the transient analysis to simulate fault conditions and switching operations associated with a system disturbance.

2.4. COMPARISON : TRANSIENT ANALYZER AND DIGITAL COMPUTER:

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 latter 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 pay 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 answers are printed when the problem is solved and partial answers can be printed during the solution to indicate progress being made toward 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 for the present and also for a number of years to come.

CHAPTER - 3

DESIGN OF THE TRANSIENT ANALYZER

3.1. GENERAL DESCRIPTION OF A TRANSIENT ANALYZER(3)

It is small scale, single phase replica of the actual system in which the voltages, currents and impedances are reproduced to a suitable and smaller scale. The results of the investigations performed may then be converted to actual values of system voltages and currents using the appropriate scale factors.

An analyzer consists of the following main component parts:

(1) Exciting Sources: A three-phase, 50 Hz, 220 V, adjustable speed, variable voltage synchronous generator for energizing the miniature system. A wave form generator for simulating lightning surges is also used for study of transient phenomena.

(2) Transmission line units, for simulating transmission line behaviour under transient conditions. Each unit consists of a constant lumped pye section whose series arm represents the inductance and resistance of the line while the two shunt arms the capacitance.

(3) Load Racks consisting of resistors of suitable ohmic range and current rating to simulate various resistive loads, losses in transmission lines or losses of other kinds.

(4) Variable Loading Reactors for simulating loads of lagging power factor or other lumped reactances.

(5) Capacitor Banks for simulating the capacitance of transmission lines and for representing capaictances used either for the improvement of power factor or raising voltage in any part of the power system.

(6) Various Recurring Synchronous Switches for performing the desired switching operations in the miniature system.

(7) A Cathode Ray Oscillograph for observing the nature and magnitude of the transient voltages and currents resulting from an imposed fault or switching condition.

(8) Oscilloscope-Camera:- A means for photographing the trace appearing on the oscilloscope-screen when a permanent record is desired.

3.2.1 EASTERN GRID NETWORK OF BANGLADESH POWER SYSTEM[21].

At present the 132 KV grid system is divided into two parts- Eastern Grid and Western Grid. An interconnection between the two grids is yet to be completed. A simplified one line impedance diagram of the Eastern Grid is shown in Plate No.1 (Page no. 18).

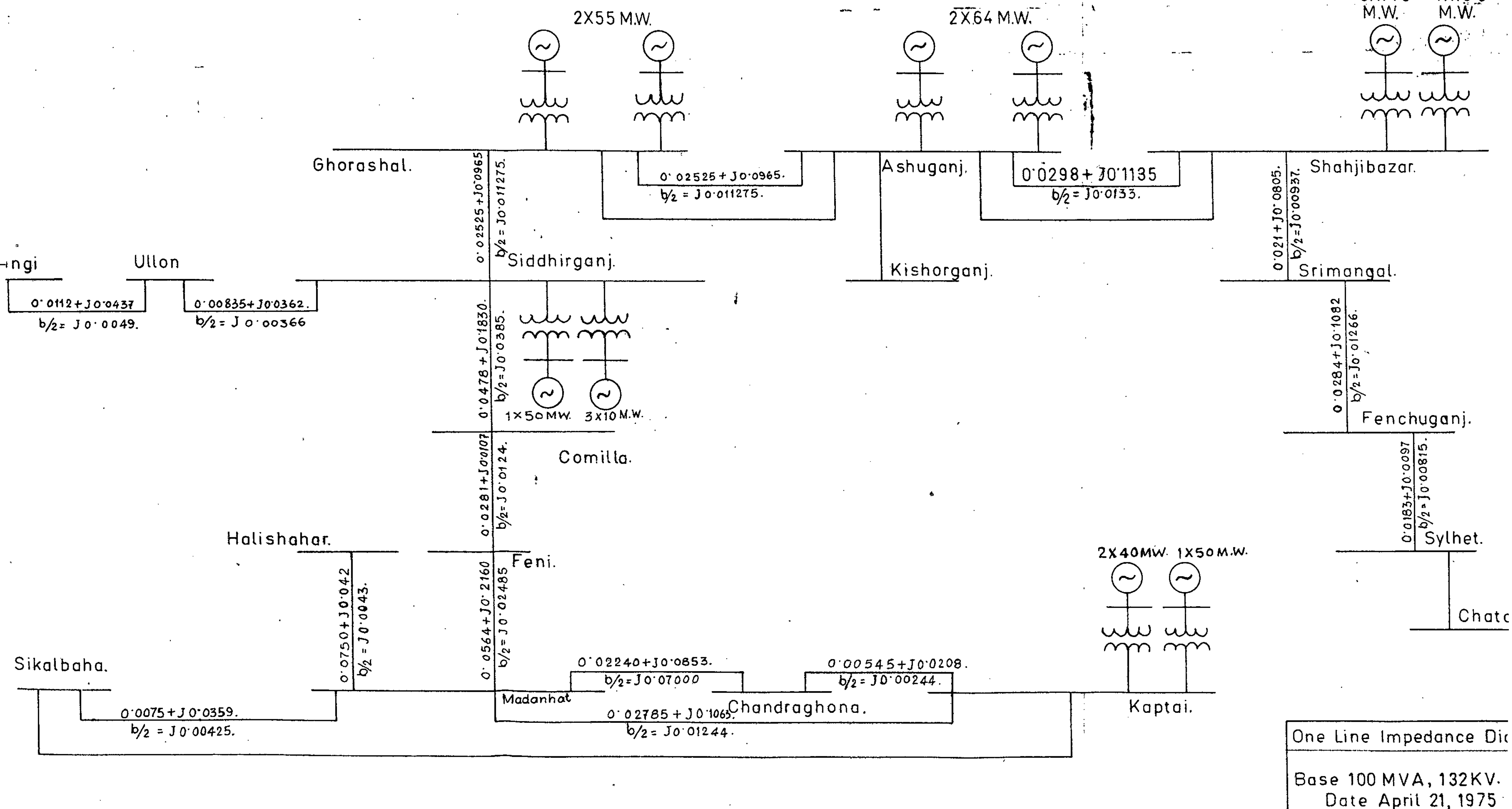
The grid consists of five major generating stations (at Kaptai, Siddhirganj, Ghorasal, Ashuganj and Shahaji bazar) and inter connected by two long transmission lines. The 170 miles long Siddhirganj-Kaptai 132 KV transmission line links Kaptai Hydrostations with Siddhirganj Steam stations and has three sub-stations located at Siddhirganj, Comilla and Modanhat and supplies power to load centres located at Chittagong, Feni, Comilla and Dacca.

The 161 miles Siddhirganj-Sylhet 132 KV transmission line links Siddhirganj Power Stations with Ghorasal, Ashuganj and Shahaji Bazar Power Stations. It has three sub-stations located at Srimongal, Fenchuganj and Sylhet and transients power to the load centres located at Tongi, Ghorasal, Ashuganj, Mymensingh and Sylhet.

The one line diagram also shows the per unit values of transmission line parameters (R,L,C) by equivalent pye -section networks on 100 MVA and 132 KV base. In the pye circuits the series

PLATE NO: 1

EASTERN GRID OF BANGLADESH. POWER BOARD.



branch has an impedance (Z) equal to the total series impedance per phase of the line. The two shunt arms, one at each end, has an admittance equal to half the shunt admittance(Y) of the line to neutral. The series impedance (Z) consists of resistance and inductive reactance while the shunt admittance consists of capacitive susceptance only.

This Eastern Grid is to be represented on the Analyzer and is the basis for the transient studies.

3.2.2 CONVERSION OF CONSTANTS FOR REPRESENTATION ON THE ANALYZER (22) (23)

To operate at a low power level the system base voltage was scaled down to 132 volt from 132 KV and base volt-ampere rating from 100 MVa to 100 Volt-ampere. The new base impedance was 174 ohms.as obtained by calculation and with these base quantities the line parameters R,L and C were calculated from their corresponding per unit values. The values of the constants together with their per unit values are shown in TABLE-1 (Page 20). For detailed calculations refer to Appendix-A. A new diagram of the Eastern Grid in terms of pye section networks is given in the figures of Plate No.2(Page No. 21).

Thus a three phase system is represented on the Analyzer on a single phase basis. 132 Volts on the Analyzer represents 132 KV line to line and 100 volt ampere on the Analyzer represents 100 MVa three phase on the system. The scales for voltage and Volt-ampere are then 1: 1000 and 1 : 1,000,000, respectively. The scales for current and impedance follow automatically from the scales chosen for voltage and Volt-ampere. In this case the base current of 0.76 amp. on the analyzer would represent 438 amp. on the actual system and the base impedance of 174 ohms on the analyzer would also represent 174 ohms on the actual system.(Appendix-A).

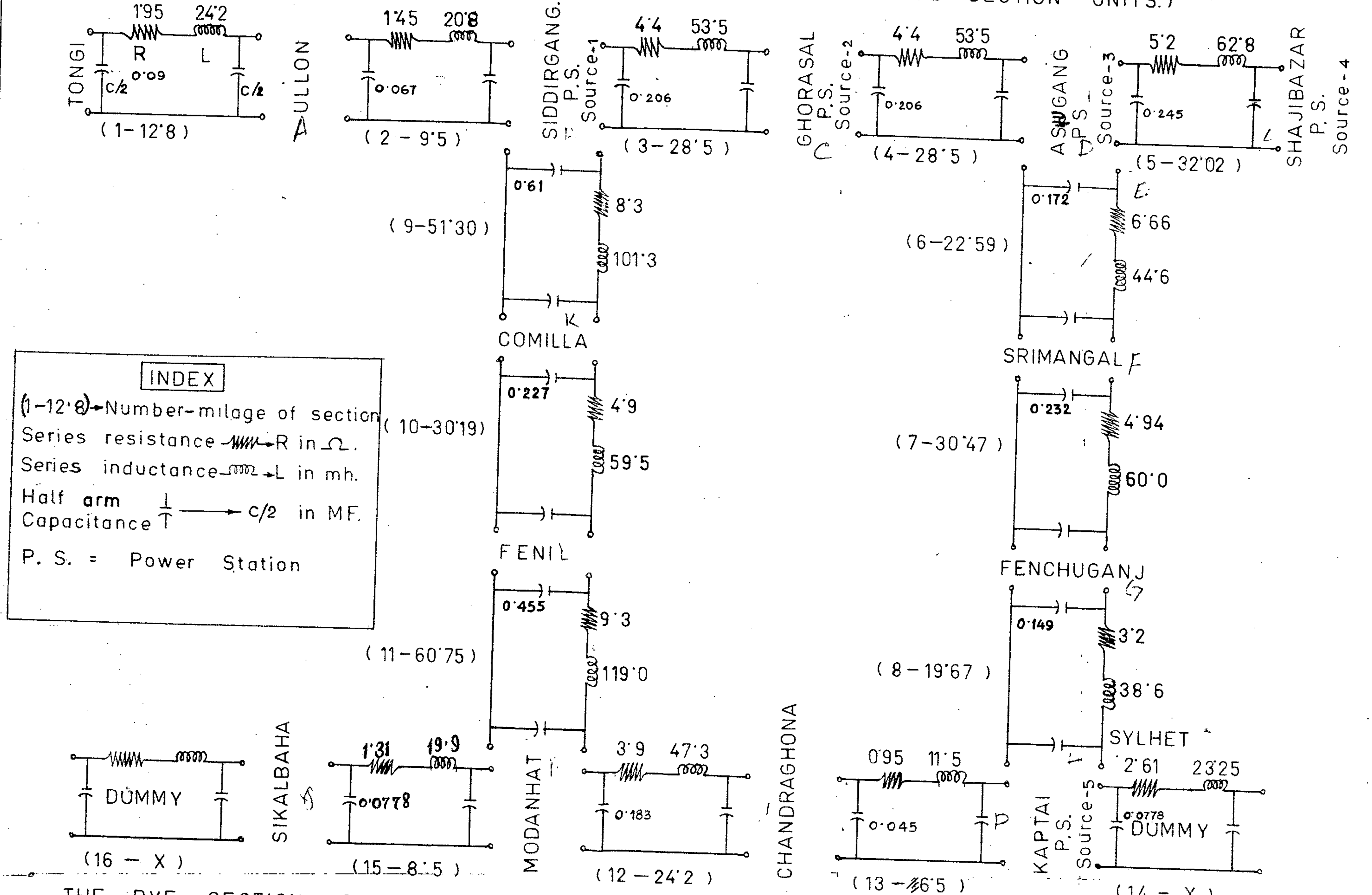
TABLE-1

TRANSMISSION LINE CONSTANTS

Section Number	Length in miles	Location of Section	P.U. Values on 100 MVa, 132 KV Base			Line Constants on 100 Va, 132V base		
			R	X_L	b/2	R (ohm)	L (mh)	C/2 (MF)
1	12.80	Tongi-Ullon	0.01120	0.0437	0.00490	1.95	24.20	0.0900
2	9.50	Ullon-Siddhirganj	0.00835	0.0362	0.00366	1.45	20.80	0.0670
3	28.50	Siddhirganj-Ghorsal	0.02525	0.0965	0.01127	4.40	53.50	0.2060
4	28.50	Ghorsal-Ashuganj	0.02525	0.0965	0.01127	4.40	53.50	0.2060
5	32.02	Ashuganj-Shahaji Baz.	0.02980	0.1135	0.01330	5.18	62.80	0.2440
6	22.59	Shajibazar-Srimongal	0.02100	0.0805	0.00935	3.66	44.60	0.1720
7	30.47	Srimongal-Fenchuganj	0.02840	0.1082	0.17150	4.94	60.00	0.2315
8	19.67	Fenchuganj-Sylhet	0.01830	0.0697	0.81500	3.18	38.60	0.1490
9	51.30	Siddhirganj-Comilla	0.0478	0.1830	0.03350	8.31	101.30	0.6135
10	30.19	Comilla-Feni	0.02810	0.1072	0.01240	4.89	59.50	0.2270
11	60.75	Feni-Modanhat	0.05640	0.2150	0.02485	9.81	119.00	0.4550
12	24.20	Modanhat-Chandragona	0.02240	0.0855	0.01000	3.90	47.30	0.1830
13	6.50	Chandraghona-Kaptai	0.00545	0.0208	0.00244	0.95	11.52	0.0446
14	15.00	Modanhat-Halishahar	0.01500	0.0420	0.00430	2.61	23.25	0.0788
15	8.50	Madanhat-Sikalbaha	0.00750	0.0359	0.00425	1.31	19.90	0.0778

PLATE NO 2

ONE LINE DIAGRAM OF EASTEN GRID.(SHOWING PYE SECTION UNITS.)



THE PYE SECTION NETWORK UNITS ARE SHOWN ALONGWITH THE PARAMETER VALUES. THE NUMBER AND LENGTH OF EACH SECTION IS ALSO SHOWN WITHIN PARENTHESIS.

3.3.1. FORMULA AND DESIGN PROBLEM WITH IRON-CORE INDUCTORS: (24) (25)

The inductance of a coil or circuit, in terms of its physical dimensions, is given by the formula.

$$L = \frac{N^2}{R} = P N^2 = \frac{N^2}{(l/\mu A)} = \frac{N^2 \mu A}{l} \qquad \text{-------(1)}$$

Where

L = inductance in henry.

N = number of turns

R = reluctance in MKS unit

P = 1/R = permeance in MKS unit

l = length of the magnitic path in metre

A = area of cross section of magnetic flux

μ = permeability of the medium and is given by

$$\mu = \mu_o \mu_r \qquad \text{-------(2)}$$

Where

μ_o = permeability of free space, 4 x 10^{-7} h/m

μ_r = relative permeability of the medium, and varies from = 2000 to 4000 for iron cored coil.

In actual practice the above formula is only a rough guide for calculation of the inductance of iron cored coils. The reason is that the inductance of any iron cored coil is a function ofthe current, because the reluctance (and in turn the permeability) varies with flux, which in turn depends upon current.

So the design of coils with magnetic cores is normally carried out by a cut-and-try process. A typical procecure is to start by assuming a core-section on the basis of previous experience. The space available for winding is allotted to the various coils to be wound on the core and a tenatative selection is made of wire size and winding details in accordance with the insulation required current to be carried, flux densities desired , The space available etc. Specially in connection with the design of such coils for a transient analyzer the space limitation, may be a crucial constriction. The performance of the resulting reactor is then evaluated and tenatative design modified as required.

3.3.2. SELECTION OF CORE MATERIALS AND WIRE SIZE FOR THE INDUCTORS

The reactance units constitute a large portion of the bulk and weight of the Analyzer. So it is important that they be made small, The value of the inductances of the most of the lines lie in the range of 20 mh to 60 mh whereas the range of resistances is 1 ohm, to 8 ohm only. Hence the reactors should have a reasonable ratio of resistance to reactance so that they can closely resemble the actual transmission lines. Further the reactance should be almost independent of the magnitude of the current in the reactor. This problem of conflicting requirements has been solved by using low base power (100 VA) and high grade laminated silicon steel as the core of the reactors.

The analyzer is designed to operate at actual system frequency of 50 Hz and has a base voltage of 132V, hence the base current is 0.76 Amp. During short circuits and switching surge simulation the current may rise momentarily to several times the base value.Hence to meet the dual requirement of relatively high current and low resistance rating, super enabled copper wire of SWG No.22 is selected. It has a steady current rating of 1.60 Amp.(which is double the base value) and a resistance value of 15.80 ohms. per 1000 ft. at 25°C.

3.3.3. APPROXIMATE TURNS CALCULATION FOR INDUCTORS.

It was decided that each of the reactor core will be built up of a stack of approximately 25 rectangular silicon steel laminations, about 0.025 inch thick per lamination. The dimension of each lamination is shown in fig.A of plate no.3 (Page 25).

The average length of the magnetic path,

$$l = 2\frac{13''}{16} + 1\frac{3''}{8} + 1\frac{15''}{16} + \frac{5''}{8} = 6.75''$$

The total thickness of 25 sheets which is also equal to the core height of each inductor

$$Th = 25 \times 0.025'' = 0.625''$$

Width of the flux path in each sheet

$$Wd = 0.55''$$

So approximate area of cross section for magnetic flux

$$A = Th \times Wd = 0.625'' \times 0.55'' = 0.344 \text{ sq.inch.}$$

The relative permeability U_r for iron core material varies from 2000 to 4000. We shall take the average value of U_r as

$$\mu_r = 3000.$$

and free space permeability

$$\mu_o = 4 \quad \times 10^{-7} \text{ h/m.}$$

Hence the permeance of the iron core comes out to be

$$P = \frac{\mu A}{l} \times \frac{4 \quad \times 10^{-7} \times 3000 \times 0.344/(39.37)^2}{6.75/39.37}$$

$$= 4.88 \times 10^{-7} \text{ mks unit.}$$

The inductance L is given by

$$L = N^2 P = \frac{N^2}{R} = \frac{N^2 \mu A}{l} = N^2 \times 4.88 \times 10^{-7}$$

Hence the number of turns required for each of the inductances is given by

$$N = \sqrt{\frac{L}{P}} = \sqrt{\frac{L}{4.89 \times 10^{-7}}}$$

Using this formula the approximate number of turns for each of the inductors was calculated as is shown in Table 2. (Page 26).

3.3.4. FORMER SELECTION AND ACTUAL WINDING OF THE INDUCTORS

For winding the coils a former of suitable size was made using thin abonite fibre of thickness 1/8". The dimension of the former was so selected that the rectangular laminated iron sheets easily fits in the former and becomes tight and compact after winding. The dimension of the former designed is shown in Fig. B of plate no. 3(Page 25)

Actual winding of the reactors were done by an automatic winding machine. During winding a suitable margin was kept between the actual no. of turns wounded and the number of approximate turns obtained by calculation. The laminated iron sheets were inserted and two screws were driven through the holes in the sheets so that the reactor becomes tight and compact. A final measurement of cross-sectional area of each of the reactors was made to take into consideration any variation in the number of the sheets. The table-3 shows the number of turns of the reactors under different conditions together with values of inductances.

3.3.5. MEASUREMENT AND CUT AND TRY PROCESS FOR GETTING THE REQUISITE VALUE OF INDUCTANCES

Measurement by Ammeter Voltmeter method : (For details of

PLATE NO - 3

Reactor core and forma

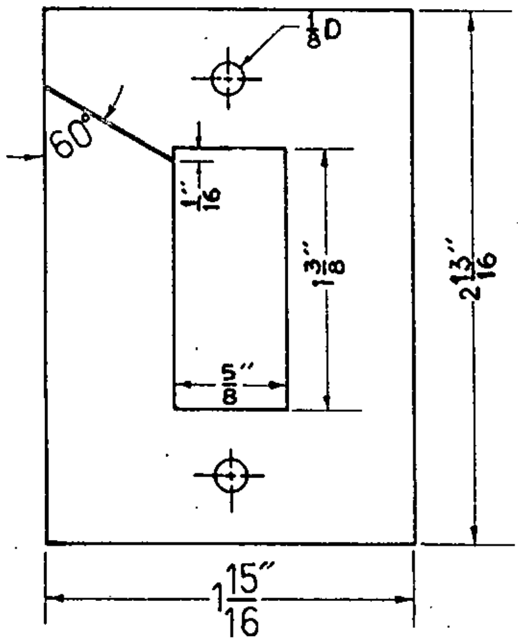


Fig. A. Reactor Core: (Rectangular steel laminaition).
Thickness of the steel sheet 0·025."

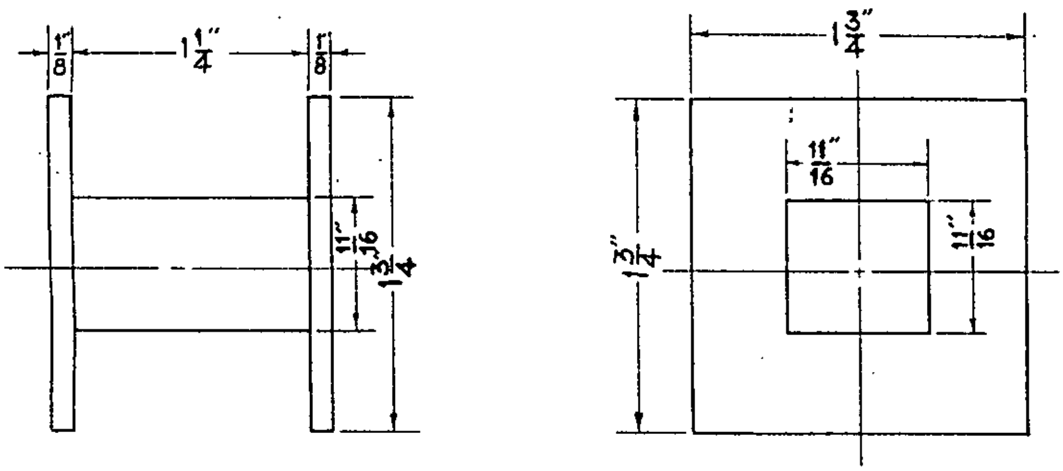


Fig. B. Foma for Reactor winding.

TABLE-2

APPROXIMATE NUMBER OF TURNS FOR THE INDUCTORS:

Serial Number	Section number	Value of inductance L(mh.)	Length of Magnetic path l(inch)	Area of cross section A(sq.inch)	Permeance p in mks unit x10^{-7}	Number of turns N
1	13	11.5	6.75	0.344	4.89	154
2	15	19.3	6.75	0.344	4.89	198
3	2	20.8	6.75	0.344	4.89	206
4	1	24.2	6.75	0.344	4.89	223
5	8	38.6	6.75	0.344	4.89	288
6	6	44.6	6.75	0.344	4.89	302
7	12	47.3	6.75	0.344	4.89	310
8	3	53.5	6.75	0.344	4.89	330
9	4	53.5	6.75	0.344	4.89	330
10	10	59.5	6.75	0.344	4.89	348
11	7	60.0	6.75	0.344	4.89	350
12	5	62.5	6.75	0.344	4.89	360
13	9	101.3	6.75	0.344	4.89	470
14	11	119.5	6.75	0.344	4.89	490

this method refer to appendix B) By applying this method the value of the inductances of the reactors designed were measured quickly and fairly accurately by passing a normal current of about One Ampere through the reactors by a voltage source.

The current flowing through the reactors was measured by an ammeter while the voltage across the coils was measured by a high resistance voltmeter. After each measurement of voltage and current for a particular reactor, the value of inductance was calculated, then according to requirement the number of turns of the reactor reduced the measurement of voltage and current and corresponding inductance calculated. The process was continued for each reactors until the required value of inductance was obtained.

Final measurement by Hay Bridge: (For details refer to appendix B). The value of the inductance of each of the reactors were then measured accurately by this bridge. It was observed that the values obtained by this method was inconformity with the values obtained by Ammeter-Voltmeter method. The variation was only ± 10%. The result is shown in Table-3 (Page-28).

3.4. SELECTION OF RESISTORS OF THE TRANSMISSION LINE UNITS.

3.4.1. Measurement of the self-resistance of the Reactors by Wheat Stone Bridge.

The a.c.resistance of the reactors at the low frequency of 50 Hz is to a close approximation, equal to the d.c.resistance of the coils.

The d.c. resistances of all the reactors were measured accurately by a wheatstone Bridge. The result of the measurement together

TABLE-3

NUMBER OF TURNS OF THE REACTORS UNDER DIFFERENT CONDITIONS WITH THEIR INDUCTANCE VALUE.

Serial no.	Section no.	Area of cross section A sq. inch.	Number of turns N			Inductance L in mh.	
			From formula	Used for winding	Final value	Actual value	Measureed value
1	13	0.314	154	200	125	11.5	12.1
2	15	0.324	198	250	102	19.9	19.3
3	3	0.346	206	250	214	20.8	21.2
4	1	0.314	223	275	133	24.2	24.2
5	8	0.309	288	350	260	38.6	38.4
6	6	0.358	302	350	219	44.6	44.5
7	12	0.368	310	350	250	47.3	47.8
8	3	0.309	330	375	220	53.5	53.5
9	4	0.331	330	375	220	53.5	53.5
10	10	0.314	348	400	327	59.5	59.5
11	7	0.352	250	490	243	60.0	60.2
12	5	0.346	360	425	260	62.8	62.5
13	9	0.314	470	550	530	101.3	101.8
14	11	0.346	490	575	480	119.0	119.5

with the resistance values of each transmission line units is shown in Table-4 (Page 30).

3.4.2. CRITERIA FOR SELECTION OF CARBON RESISTORS USED.

An external resistor of required value was connected in series with each reactors to obtain the actual resistances of each line units. In general, for this purpose wire wound resistors would be preferred - But for non-availability of suitable wire wound resistors we had no alternative but to use carbon resistors.

In selecting the carbon resistors attention was given to its wattage rating in addition to the resistance value. This was necessary so that the carbon resistors could carry the normal current without much heating. Precision resistors were searched for closely simulating the resistors of each unit. But we had to remain satisfied with available 10-20% tolerance resistors, thus allowing minor variations.

Exact resistance values required for each unit could not be obtained. By series combination of a number of resistors , a value very near to the required value of the unit was simulated accepting 10% fluctuations. The resistors used in different combinations and the difference between actual value and the simulated values are all shown in Table -4 (page 30).

TABLE-4

RESISTANCE OF TRANSMISSION LINE UNITS

Serial no.	Section no.	Resistance of each unit R in ohms.	Resistance of each inductor unit R in ohms.	External resistance required R_{ex} in ohms.	Carbon resistance added R in ohms.	Types & No. & tolerance of carbon resistors.
1	13	0.95	0.28	0.67	0.68	1w.10%
2	15	1.3	0.40	0.90	0.82	1w,10%
3	2	1.45	0.42	1.03	1.00	1w,20%
4	1	1.94	0.46	1.48	1.50	1w,10%
5	8	3.20	0.70	2.50	2.70	2w,10%
6	6	3.60	0.73	2.93	3.02	(2.2,2w,10% (0.82,1w 20%
7	12	3.90	0.94	3.00	3.3	2w,10%
8	3	4.40	0.80	3.60	3.3	2w,10%
9	4	4.40	0.80	3.60	3.3	2w,10%
10	10	4.90	1.05	3.85	3.86	(3,3,2w,10% (0.56,1w,10%
11	7	4.94	1.0	3.94	3.90	(2.7,2w,10% (1.2,1w,10%
12	5	5.20	1.06	4.14	3.9	2w,20%
13	9	8.31	1.7	6.60	6.7	(1.8,2w, 10% (2.2,2W 10% (2.7,2W, 10%
14	11	9.80	2.6	8.20	7.8	2x3.9,2w,20%

3.5. SELECTION OF CAPACITORS FOR THE TRANSMISSION LINE SECTIONS

Each pye-section unit of transmission lines has **two** shunt arms one at each end and each shunt arm has half capacitance value of the section.

The capacitances of different section lies in the range 0.045 mF to 0.61 mF. as is seen from Table-5(Page 32).

For durability, relatively small size, ensuring compactness of the system, paper capacitors were used. In addition to the capacitance rating attention was given to the voltage rating and tolerance of the capacitors. Although system exciting voltage was 132 V A.C, during switching operations the voltage surges may be several times the steady value. Hence minimum working voltage of the capacitors used was 600V, although most of them had 1000 working voltage.

Exact values of capacitance for each section was not available. Hence by parallel combination of a number of capacitors a value close to the required value was simulted allowing 10% variations. The capacitors used with their voltage rating and numbers are shown in a tabular form. (Refer- Table-5) (Page 32).

TABLE-5

CAPACITANCES OF THE TRANSMISSION LINE UNITS:

Serial Number	Section number	Capacitance of one shunt arm C in mfd.	Total value of capacitance of one arm of each section C in mfd.	Number & values of capacitors used for both arms C in mfd.
1	13	0.045	0.050	2x0.05,1000v
2	15	0.0778	0.072	2x0.05,1000v 2x0.022,1000v
3	2	0.067	0.072	2x0.05,1000v 2x0.022,1000v
4	1	0.090	0.10	2x0.10,1000v
5	8	0.149	0.15	2x0.10,1000v 2x0.05,1000v
6	6	0.172	0.17	2x0.12,1000v 2x0.05,1000v
7	12	0.183	0.17	2x0.12,1000v 2x0.05,1000v
8	3	0.206	0.20	2x0.10,1000v 2x0.10,1000v
9	4	0.206	0.20	2x0.10,1000v 2x0.10,1000v
10	10	0.227	0.22	2x0.12,1000v 2x0.10,1000v
11	7	0.232	0.22	2x0.12,1000v 2x0.10,1000v
12	5	0.2438	0.25	2x0.25,600v
13	9	0.610	0.60	2x0.30,600v 2x0.30,600v
14	11	0.455	0.42	2x0.30,600v 2x0.12,1000v

3.6. DESIGN OF THE PANEL BOARD AND MOUNTING OF THE COMPONENTS:

A panel board was designed and constructed so that all the circuits units and other accessories could be readily connected together in any desired manner to form a network representing a particular power system. The different sectional views along with their specifications are shown in **Figures** of plate no.4(Page 34).

The transmission line units are mounted on the tapering side of the triangular board. Each pye-section network terminates in a pair of inter connected socket on both ends. This arrangement helps easy interconnection and insertion of oscilloscope and other measuring instruments including exciting sources wherever necessary. Each unit is isolated but as many units can be connected together as desired.

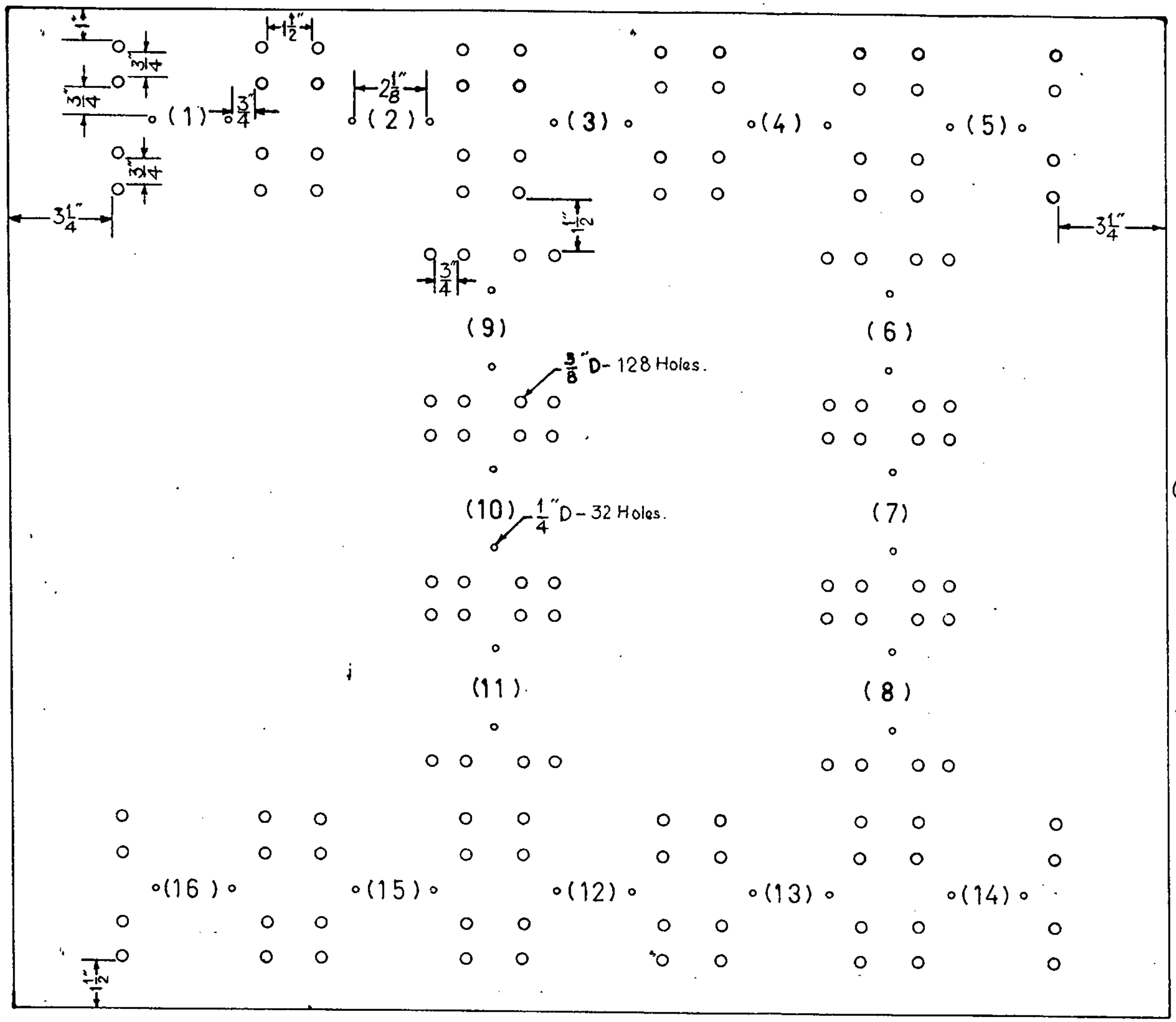
3.7. DESCRIPTION OF OTHER COMPONENTS OF THE ANALYZER.

(1) Exciting Sources:

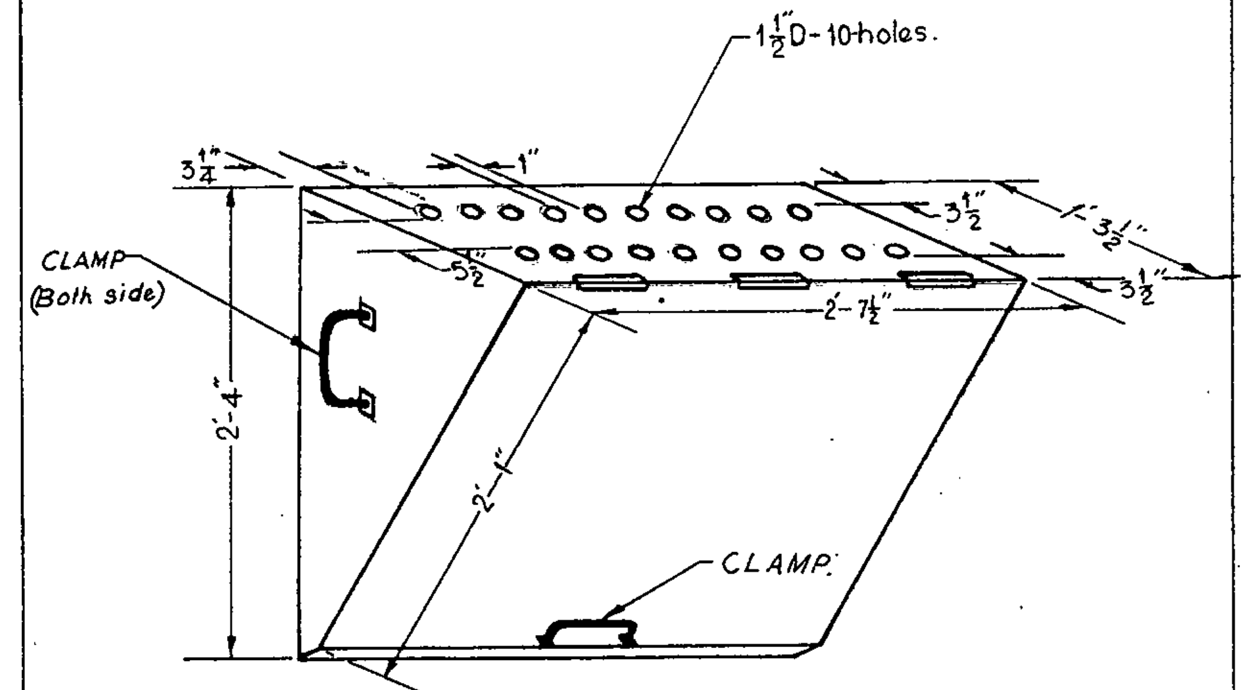
The 3-Ø, 50 Hz, 220v variable speed generator required for the Analyzer will be the synchronous generator of AEG generalized machine set of Power-System Laboratory. A 125V D.C. shunt motor is used as the prime mover of this generator. The field excitation is also provided by 125V d.c. The terminal voltage of the synchronous generator is controlled by a field rheostat in series with the generator-field circuit. An output voltage of desired magnitude from any two terminals of the generator can be applied across any terminal pair of the Analyzer as desired.

The pulse generator for simulating lighting surge was a Hewlett Packward (HP) square wave generator available in the laboratory. The pulse magnitude can be varried from 0-7V continous.

PLATE NO: 4
DESIGN SPECIFICATION OF THE PANEL BOARD



FRONT VIEW



ISOMETRIC VIEW. (PANEL BOARD)

The square pulse can be obtained at an input impedance of 400 ohms or 60 ohms. as desired. The pulse repitation rate is adjustable from 5 PPS to 20 KPPS.

(2) Arrangement for Different Loads:

For simulating resistive loads Laboratory load racks with 2.2 A current & 2 KW power rating were used. The load variation in 10 ohms. steps from 0 to 1000 ohms was possible. Inductive loads were simulated with loading Reactors rated at 3 KVa, 240V and 25A with variations insteps of 0.5A, 1A, 2A and 4A. Capacitor Banks with capacitance from 0-31 mF rated at 250 A.C. were used for capacitive load simulation. Variation was made in steps of ½ mF, 1 mF, 2 mF etc. as required.

(3) Measuring Instruments:

Cathode Ray Oscillograph: A special Tetronic Oscilloscope with storage facilities was used. This facilitated the observation of the nature and magnitude of the transients arising as a result of simulated fault conditions and switching and lighting surges. Provision was made for eliminating certain portions of the trace from the screen, leaving only the portion desired for observation. In addition special arrangement is made in the sweep synchronizing circuit to control the position of the trace on the screen. Storage facilities are provided to facilitate taking photographs for permanent records.

An ammeter and a voltmeter are also provided for recording steady state voltage and currents during normal load flow and under different fault conditions and switching operations.

(4) Photographic equipment: An oscilloscope Camera was used for photographing the trace appearing on the screen for permanent records.

CHAPTER - 4

VOLTAGE TRANSIENTS AND LINE SURGES IN POWER SYSTEMS

4.1. BACKGROUND:[30]

There are various ways in which a transmission line may experience transient overvoltages greater than the working value. So it is necessary to provide protective apparatus to prevent or minimize the destruction of the plant.

Internal causes producing a voltage rise are (1) resonance, (2) switching operations, (3) insulation failure and (4) arching earths.

A very important external cause is lightning.

4.2. RESONANCE PHENOMENA:

Over voltages due to resonance on power systems are usually of the form of (1) resonance or partial resonance at the system natural frequency ($W_n = \frac{1}{\sqrt{LC}}$) consisting of the system inductance and capacitances. (2) Ferro resonance phenomena.

4.2.1. NATURAL FREQUENCY RESONANCE[30]:

The effect of this type of resonance is most easily explained by considering the voltage at the end of a lightly loaded cable of short length. The alternator and transformers may be represented by their leakage inductance L, and the cable by a capacitance C. The system is then as shown in Fig. 1a, where R represents the resistance of the alternator winding, transformer and cable, and r the resistive load. The total impedance of the circuit is

$$Z = R + JwL + \frac{(1/JwC)r}{1/JwC + r} = R + JwL + \frac{r}{1+JwCr} \quad \ldots (1)$$

and the current is

$$I = E/Z, \qquad (2)$$

and the voltage on the cable is

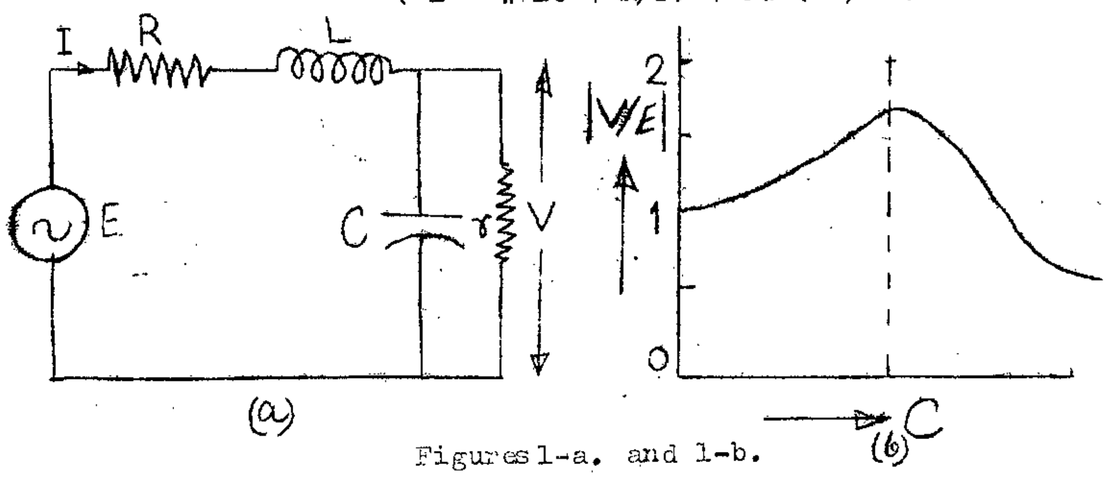
$$V = I \times r/(1+JwCr), \qquad \ldots\ldots\ldots\ldots(3)$$

Since the latter expression represents the impedance of the parallel combination of C and r. Substituting for I in terms of E we get

$$|V/E| = \left(\frac{r}{1 + JwCr} \right) \Big/ \left(R + JwL + \frac{r}{1+JwCr} \right)$$

$$\doteq \frac{1}{1 + (R + JwL)\,(1/r + JwC)}$$

$$= \frac{1}{(1 - w^2LC + R/r) + Jw\,(L/r + CR)} \qquad \text{------}(4)$$



Figures 1-a. and 1-b.

The magnitude of (V/E) is

$$|V/E| \doteq \left((1 - w^2LC + R/r)^2 + w^2(L/r+CR)^2 \right)^{-1/2} \qquad \ldots\ldots(5)$$

Let us consider the case of an unloaded line first. In this case r = , so that

$$|V/E| = \left((1-w^2LC)^2 + w^2C^2R^2 \right)^{-1/2} \qquad \ldots\ldots\ldots\ldots(6)$$

If we consider that C can vary, by the insertion of different lengths of cable, |V/E| varies in the manner shown in Fig. 1-b.

The maximum value occurs when

$$C = \frac{1}{w^2L + R^2/L} = \frac{1}{w^2L\,(1 + R^2/W^2L^2)} \simeq \frac{1}{w^2L}$$

When $\not{} |V\not{}E|$ $= \frac{1}{wCR \quad ((1 + R^2/w^2L^2))^{1/2}} \simeq \frac{1}{wCR} \simeq \frac{wL}{R}$ ....(7)

A resonable value of L in a ~~132~~ 33KV KV system is 0.05 henry, and the resonating capacitance is then

$$C = \frac{1}{(2\quad .\ 50)^2 \times 0.05} = 202\ MF.$$

Which ~~is~~ is the capacitance of some hundreds of miles of cable. Resonanace in short lines will thus never occur at the fundamental frequency. Ig we consider the 5th harmonic , which is often present to the extent of 2 or 3 percent, we see that resonance can occur. The capacitance required is

$$C = \frac{1}{(2\pi\ .250)^2 \times 0.05} = 8.1\ mF$$

which is provided by a cable of about 30 miles. Ig we assume a 10 percent harmonic the value of V_5 is

$$|V_5| = |E_5| \times 2\pi \times 250\ L/R = 0.10 \times |E_1| \times 2\pi \times 250\ L/R,$$

where E_1 is the fundamental, and E_5 the 5th harmonic. Ig we take R = 5 ohms, we findthat

$$|V_5| = 1.57 \times |E_1| \quad ,$$

So that the fundamental voltage of

E_1 = 33 KV

has a fifth harmonic of magnitude-

$|V_5| = 52$ KV (rms).

The peak value between phases may than be

$$\sqrt{2} \times 85 \text{ KV}$$

in place of the normal value of

$$\sqrt{2} \times 33 \text{ KV}.$$

The effect of a load is seen by comparing equations (5) and (6). It is seen that the term (R/r) is an additive constant in the first term on the right hand side of the equations and alters the condition for the neutralization of reactance, whilst the term (L/r) causes a considerable damping of the resonance. Let us take r = 200 ohms, which corresponds to a load of 5000 Kw, then with the values of L,C and E_5 taken above, we find that

$$1 - w^2LC + R/r \simeq 5/200 = 0.025$$

and $w(L/r + CR) = wCr\ (1 + L/C\ Rr\ ) = 7.2wCR = 0.46$.

The 1st term is thus negligible compared with the second, so that we may take

$$|V_5/E_5| \simeq \frac{1}{w(1/r + CR)} = \frac{1}{7.2wCR} \simeq \frac{wL}{7.2R}$$

So that V_5 is reduced by the factor 7.2 and has a magnitude of 52/7.2 = 7.2 KV. The resonance voltage has been therefore effectively damped by the load.

4.2.2. CONDITIONS FOR NATURAL FREQUENCY RESONANCE(4)

The natural frequency resonance may occur in the system under one or more of the following conditions.

(a) In transmission and distribution networks, if an extended underground cable system, a predominant capacitance is fed by long distance overhead lines and transformers of predominant inductance. In this case, the natural frequency may easily be of the order of a lower harmonics (only 5th or 7th harmonics have importance) of the generator voltage and thus may cause excess voltages in the entire system.

(b) Feeder cables of high capacitance, which are protected against short circuits by series reactors of high inductance, may also give rise to resonance phenomena.

(c) Static condensers, frequency used to improve power factor of networks, also may form resonance circuits with the feeding transformers, particularly at no-load of the circuit, where no resistance damping is present.

With every alteration in the curcuits of the system because of faults and ever with every variation of the loads by switching operations, the capacitances and inductances of an actual network change substantially. In practice, it is found, therefore that disturbance by resonance occur at certain conditions in the power system giving rise to excessive overvoltages and may again disappear with change in the distribution of the load or in the interconnection of the system circuits.

However, the most reliable means for avoiding any resonance voltage and current consists in the generation of sinusoidal voltage, as pure in form as possible. Hence it is desired that the feeding alternators should produce no considerable harmonics either at load or no load condition.

4.2.3. FERRO RESONANCE[27]

Ferro resonance occurs when the unsaturated inductance of the transformers is greater than the circuit capacitance to ground and some transient conditions results in a temporary high current causing the iron to saturate; this causes the inductive reactance to decrease and approach the capacitive reactance, creating a resonant condition called ferro resonance. The system voltage and current under these conditions is not periodic but rather fluctuates wildly as the current swings back and forth between lagging and leading power factor , as it moves in and out of the resonanant condition.

4.3.1. SWITCHING SURGES[30]

A switching operation produces a sudden change in the circuit conditions, and is accompanied by a transient state which leads from one steady states to anoth r steady states. The behaviour of the system can be explained with exactness only by means of travelling waves; but in short systems the behaviour is sufficiently well explained if we consider the circuit to be composed of lumped resistances, inductance and capacitances.

4.3.2. TRANSIENTS IN CIRCUITS WITH LUMPED CONSTANTS[30]

There is an interesting case which we shall solve, the switching-in of an open circuited line.

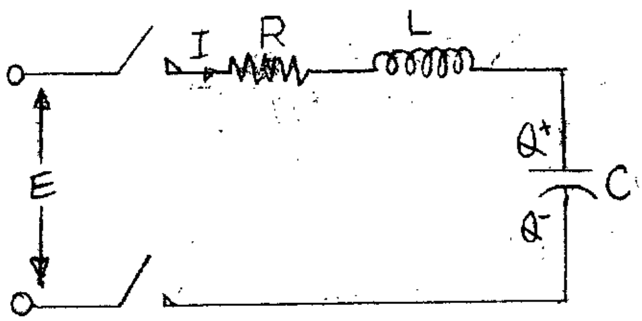


Fig.2-A Switching in of an open circuited line.

We assume for simplicity that the system emf is constant and equal to E. The equation for the current is

$$L \frac{di}{dt} + Ri + Q/C = E \qquad \ldots\ldots\ldots\ldots\ldots\ldots(8)$$

where $i = \frac{dQ}{dt}$

The voltage at the end of the line is

$V = Q/C$, substituting for i, in terms of Q we get

$L\,(d^2Q/dt^2) + R\,(dQ/dt) + Q/C = E$, the solution of

which is

$$Q = CE + e^{-(R/2L)\,t}\,(\,A \cos\alpha t + B \sin\alpha t\,)$$

Where $\alpha = ((\,1/LC\,) - (R^2/4L^2))^{1/2}$, and A & B are constants which are determined by the initial conditions. At the instant, $t = 0$, of switching-in Q and i are zero. These conditions give

$$A = -CE \text{ and } B = AR/2L\alpha \,.$$

So that

$$V = Q/C = E - Ee^{-(R/2L)t}\,(\,\cos\alpha t + (\,R/2L\alpha)\,\sin\alpha t) \qquad \ldots\ldots\ldots\ldots(9)$$

and $i = \frac{dQ}{dt} = (E/(\alpha L))\,e^{-(R/2L)\,t}\,\sin\alpha t.$ $\qquad \ldots\ldots\ldots\ldots(10).$

If the resistance is negligible the voltage and current reduce to

$$V = E\,(\,1-\cos\,(\,t/\sqrt{LC})\,) \qquad \ldots\ldots\ldots(9a)$$

and $$i = (E\sqrt{(C/L)}\,)\,\sin\,(t\,/\sqrt{(LC)}\,) \qquad \ldots\ldots\ldots(10a)$$

Since $\alpha = 1/\sqrt{(LC)}$ in this case.

The voltage in this case oscillates sinusoidally between 0 and 2E, whilst the current is a sine wave of peak value $E/\sqrt{(C/L)}$.

Fig. 2-B shows the voltage and current for the case of no resistance (curves A) and for some resistance (curves B)

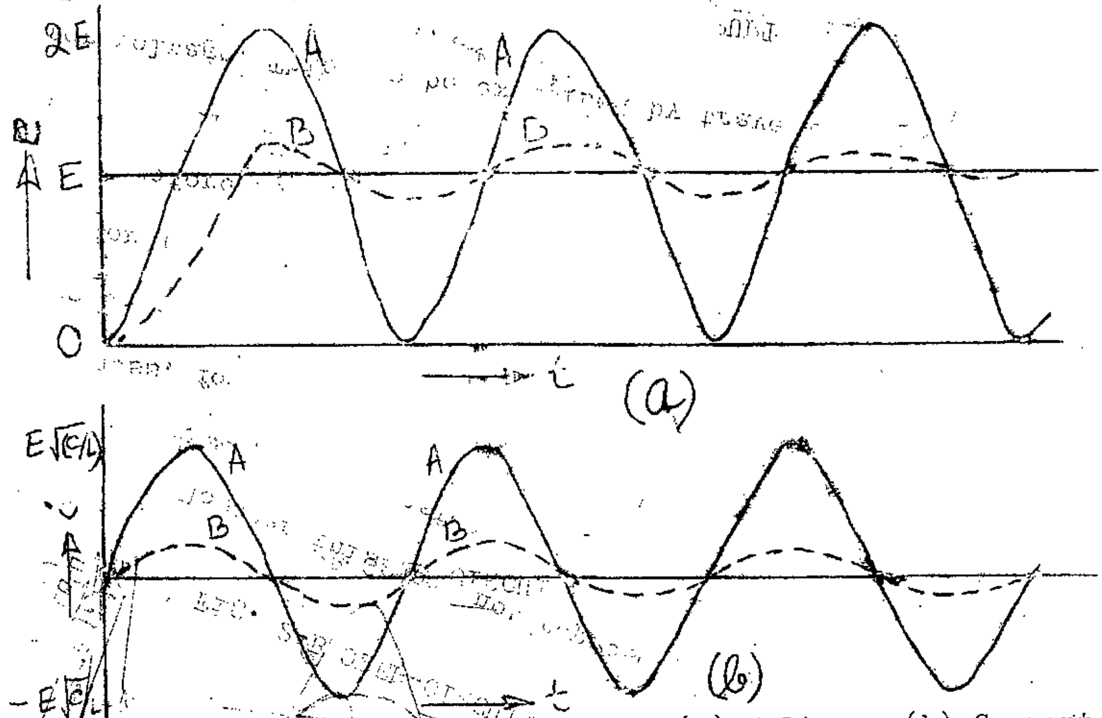


Fig. 2-B OPEN-CIRCUITED LINE (a) Voltage, (b) Current.

However this does not represent the state of affairs with exactness, for any transfer of energy must travel with a velocity less than that of light, so that the far end of a line is unaffected for the finite time that it takes the energy wave to reach it. It therefore follows that part of the line may be passing current and maintaining a voltage whilst a further part has neither current nor voltage. This can be explained by travelling wave theories.

4.3.3. TRANSIENTS DURING SUDDEN INTERRUPTION OF A CIRCUIT(30)

Suppose that a circuit has a current i, which is suddenly interrupted by the circuit breakers S, S (Fig. 3). The disturbance produces two travelling waves moving from S, S to the right and to the left. The wave travelling to the right has a current -i and must therefore have a voltage -E, where E= iZ; line A is therefore -E volts above line B. The wave travelling to the left has a current -i, and must therefore have a voltage + E, where E = iZ; Line C is therefore + E volts above Line D.

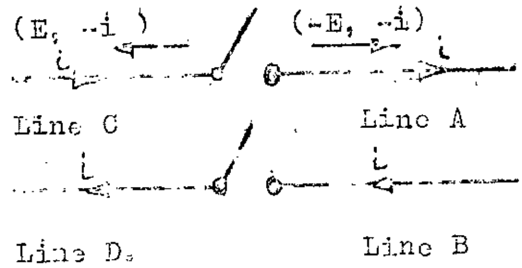


Fig. 3 sudden interruption of a circuit.

These waves progress in a normal manner until they meet sh... changes in the line, when, they are reflected and transmitted a... well. It should be noted that if only one break is made, so that B and D are always commoned, the voltage between A and C is 2 E.

The surge voltage E is super-imposed on the normal voltage ... that part of the line which remains connected to the generator.

4.3.4. SURGES DUE TO INSULATION FAILURE OR EARTHING OF A LINE.(30)

Suppose that a line AB, at potential E, is earthed at a point P. The effect of earthing is to introduce a voltage - E to P, and two equal waves of voltage -E travel along PA and PB. The wave travelling to the right has a current of - E/Z, and that to the left ... these currents pass through P to earth, so that the current to earth is 2E/Z. Fig. 4 shows the waves and currents in the system.

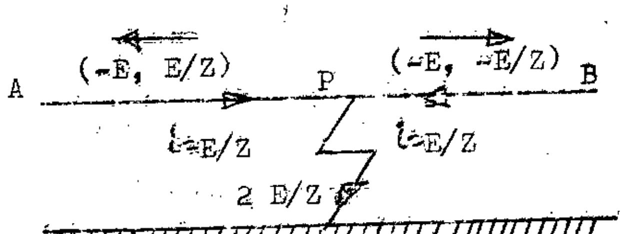


Fig. 4 Surges due to a failure of insulation.

As these waves travel to the ends of the line they reduce the voltage to zero and when they reach the open ends, reflected waves are set up which reduce the voltage to E-E-E, i.e.-E, and the current is neutralized. When the reflected waves reach P, the portions of the line along which they have travelled will be changed to -E. The current at P can be reversed by a flashover in the opposite direction, and the result is a periodic flash-over with reversals of potential on the line and currents at P until the stored emergy is dissipated by damping.

4.3.5 : PROPAGATION OF SURGES IN A LINE TERMINATED BY A FINITE IMPEDANCE(30)

Suppose that a travelling wave (E, i) moves along a line of surge impedance (Z) and meets a termination of resistance R (Fig.5). 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.

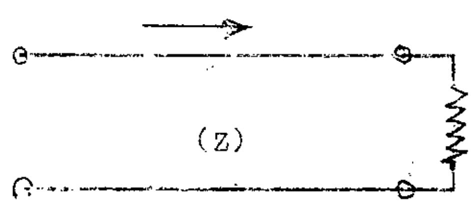


Fig.5 Line Terminated on a Resistance R.

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 $i' = \left((Z - R) / (Z + R)\right) i$ ....(11a)

and $E' = -\,i'Z = \left((R - Z) / (Z+R)\right) E$ ....(11b)

The total current and voltage are

$i + i' = \left(2Z / (Z + R)\right) i$ ....(12a)

and $E + E' = \left(2R / (Z + R)\right) E$ ....(12b)

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

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 (11) and (12), 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.

4.3.6. SURGES AT THE JUNCTION OF TWO LINES:

Figure 6 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 right - hand line can be considered to have an impedance ZB, so that the case is the same as that shown in Fig.5; provided Z is replaced by Z_A and R by Z_B .

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

$$i' = \left((Z_A - Z_B) / (Z_A + Z_B)\right) i \qquad \ldots\ldots\ldots(13a)$$

and
$$E' = \left((Z_B - Z_A) / (Z_A + Z_B)\right) E \qquad \ldots\ldots\ldots(13b)$$

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

$$i'' = i + i' = \left(2 Z_A / (Z_A + Z_B)\right) i \qquad \ldots\ldots(14a)$$

and
$$E'' = E + E' = \left(2 Z_B / (Z_A + Z_B)\right) E \qquad \ldots\ldots(14b)$$

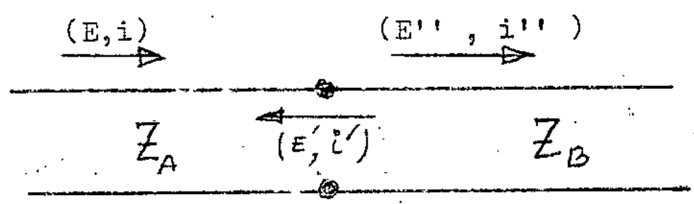


Fig.6 Junction of 2 lines.

The reflected and transmitted waves at a point where a line forks. (i.e. Junction of three lines). Fig.7 represents the arrangement schematically. The surge impedances are Z, Z_1, and Z_2 respectively.

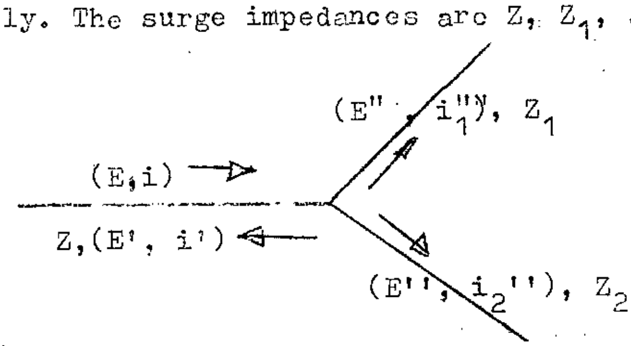


Fig. 7 Travelling waves at a junction of 3 lines.

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 (15).

$$E = iZ$$

$$E' = -i'Z$$

$$E'' = i_1'' Z_1 \qquad \text{.........(15)}$$

$$E'' = i_2'' Z_2$$

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

$$i + i' = i_1'' + i_2'' \qquad \text{............(16)}$$

The voltage at the junction is

$$E + E' = E'' \qquad \text{.........(17)}$$

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 voltages we see that equation (16) becomes

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

adding this to equation (17) we get

$$2E = E'' \times (1 + Z/Z_1 + Z/Z_2),$$

So that the voltage at the fork is

$$E'' = 2E/(1 + Z/Z_1 + Z/Z_2) = 2E(1/Z)/(1/Z + 1/Z_1 + 1/Z_2) \qquad \text{..........(18)}$$

The transmitted currents 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

$$E' = E'' - E = \frac{E(1/Z - 1/Z_1 - 1/Z_2)}{(1/Z + 1/Z_1 + 1/Z_2)} \quad .....(19)$$

and the current is

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

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

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

4.3.7. EFFECT OF CAPACITANCE ON SURGE VOLTAGE[30]

Suppose that a wave (E.i) meets a termination composed of the parallel combination of a capacitance C and resistance R as shown in Fig.8.

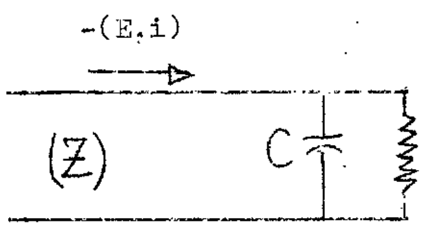


Fig.8

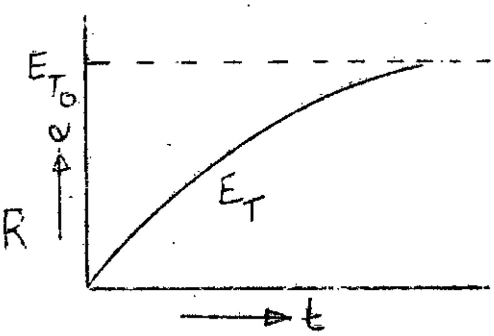


Fig.9

The problem is the same as that shown in Fig.5, except that R in equations (12) must be replaced by

$$(1/pC)\,R \Big/ (1/pC + R) = R/(1+pCR),$$

Where P = d/dt,

The voltage at the termination is thus

$$E_T = E + E' = \frac{2R/(1+pCR)}{Z + R/(1+pCR)} \times E \quad \ldots\ldots\ldots (20)$$

It must be remembered that P = d/dt and E is a voltage which is zero until t =0 and E, after t =0. Solution of equation(20), gives E_T as

$$E_T = E_{T_o}\left(1 - e^{-\left(\left(Z+R\right)/C\,ZR\right)t}\right),$$

where E_{T_o} is the voltage at the end when there is no capacitance.

Fig.9 shows the graph of E_T. The effect of the capacitance is to cause the voltage at the end to rise to the full value gradually instead of abrruptly, i.e. it flattens the wave front. Flatenning the wave-front has a very benificial effect, as it reduces the stress on the line-end windings of a transformer connected to the line.

4.3.8 EFFECTS OF SWITCHING SURGES ON SYSTEM AND EQUIPMENTS INSULATION(26,27)

The operation of system circuit breakers to connect and disconnect equipments and transmission lines creates switching surge transients that could cause equipment failure. The severity of a transient in a given switching operation depends on the circuit breaking device as well as the circuit parameters.

The opening of the contacts of a Circuit-Breaker involves current flow interruption, which creates a recovery voltage across the opening contacts. If the design of the device is such that the dielectric recovery across the contacts is slower than the recovery voltage build up, a restrike will occur creating a switching surge.

The characteristics of this surge voltage are a high amplitude, which may reach 3 to 4 times that of the system voltage and a relatively high frequency. This voltage is, in effect, injected into the circuit at the breaker terminals and travels along the line in both directions.

In practice resistance and crona effects quickly reduce the magnitude as the wave travels along the line, but the effect on insulation at points close to the circuit breaker is of importance; as also the possibility of restrike at the breaker contacts.

With the advent of extra high voltage (EHV) system the peak value of the restriking voltage may approach a dangerously high value. The effects of the restriking transients are therefore extremely important from the insulation point of view; The severity of the duty imposed upon insulation is likely, in the case of these high voltages, to be equally if not more significant than that due to induced lightning disturbances.

During opening a circuit breaker, the most severe restrike occurs when the voltages on either side of the contacts reach 180° seperation such as in the case of a near-end switching of a transmission line with the far end breaker open.

During a closing operation of a circuit breaker, the severity of the transients depends not on the CB design, but rather on the circuit parameters and the phase angle of the voltage when the CB completes the circuit. The closing operation of a CB is assumed to initiate a surge when closing with the voltage, is done at maximum value. The most severe closing switching surge can be initiated by closing-in on a system 180° out of phase with the system on the other side of the breaker. This closing condition is equivalent to the opening condition of one restrike.

The basic transient equations(27) for switching -surge analysis are, for closing and opening a switch, respectively.

$$i_{sw} = e_{before\ sw} / Z(p)_{sw} \qquad ....(1)$$

and $$e_{sw} = i_{before\ sw} \times Z(p)_{sw} \qquad ....(2)$$

Where $e_{before\ sw}$ is the negative of the voltage across the open switch at the instant before closing; and $i_{before\ sw}$ is the negative of the current through the switch just prior to the openings the switch. $Z(p)_{sw}$ in both equations is the impedance of the system as seen through the switch terminals.

The over voltage resulting from switching is the steady state voltage prior to switching with the transient voltage superimposed, i.e.

Resultant voltage = steady state voltage +

+ Transient voltage.

4.4.1. NATURE OF LIGHTNING SURGES (2),(26),(27)

Lightning surges arise as a result of the action of lightning discharge upon electrical installations. The maximum possible amplitude of these surges has no direct relationship to the operating voltage of the system and their danger increases with the decrease in the working voltage.

A lightning discharge takes place when a cloud is raised to such a high potential with respect to earth(or to a neighbouring cloud) that the insulating property of the surrounding air is destroyed . This raising of potential is due to frictional effects caused by atmospheric disturbances acting on the particles forming the cloud.

A lightning stroke to a line creates a travelling wave, which is infact the static energy in motion due to a concentration of this energy at one point in a system, Usually the discharge is from cloud to earth, but where tall objects are involved, the discharge is frequently from earth to cloud. The transmission lines frequently provide the easiest path for the cloud charge to dissipate itself into the earth and therefore are frequently hit by lightning.

The character of the surge to be used in an analysis depends partly on the initial discharge, that is, the amount of static charge in the cloud, but it also depends on where it hits the line and the type of the line.

Accordingly lightning surges may be divided into two kinds-

(1) Induced charges and

(II) Surges due to direct strokes of lightning.

4.4.2. EFFECTS OF LIGHTNING SURGES ON EQUIPMENTS AND SYSTEM INSULATION[2],[26]

Induced surges are created by discharge of lightning which occur near the affected electrical installation or transmission line. They are the result of electrostatic induction. The current that will flow during a lightning discharge from a cloud to earth or through some structures to earth in most cases will have a crest value of 10-25KA, but may reach values as high as 200-250KA(corresponding power to be dissipated is 10^{10}KW), **and the tail of the wave may last a second or longer.**

An induced surge will usually have an amplitude of several hundred KVs. The minimum short time (Impulse) electric strength of the insulation (BIL) in installations of 132KV and higher voltage is generally not less than 300-600KV, that of 33KV installations is of the order of 180-200KV. Because of this, induced lightning surges are a source of serious danger for 33KV installations and lines, but are not so dangerous for circuits and installations with working voltages of 132 KV and higher.

When a direct stroke of lightning strikes a transmission line or an outdoor substation circuit or unit, then the power to be dissipated in the short time in which the discharge takes place may be of the order of 10^{10} KW. Thus it causes a very large current (upto 250KA) to flow. It creates an extremely high surge of voltage, the value of which in some cases will exceed the normal working voltage by several tens of times. Direct lightning surges are hence the most severe and dangerous form of disturbance experienced by the insulation of transmission lines and equipments associated with them.

In either of the cases (induced surge or direct stroke surge) the waves set up can usually be represented as the difference of two exponentials[26], thus

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

Where a and b are constants which determine the shape. A wave of this type is shown in the figure of plate no.5A (page-56).

Such a wave is used for testing purposes when it is necessary to investigate the behaviour of power systems under conditions of this type. The wave is designated by the time t_1, taken to attain maximum value, and the time t_2, taken for the tail to fall to 50% of the maximum value. The wave chosen for testing purposes is generally 1/50 wave which implies that t_1 is 1 micro second and t_2 is 50 micro second.

4.5.1. ARCHING GROUND FAULTS:[30]

In the early days of transmission it was the practice to insulate the neutral point of three phase lines, for then an earth on one phase would not put the line out of action; this also eliminated the longitudinal (or zero sequence) current and resulted in a decrease of interference with communication lines. Insulated neutrals gave no trouble with short lines and comparatively low voltages, but it was found that when the lines become long and the voltages high (HV) a serious trouble was caused by ARCHING EARTHS, which produced a severe voltage oscillations of 3 to 4 times the normal voltage. These oscillations were cumulative and hence very destructive. Arching earths are eliminated either by solid earthing of the neutral or the neutral is earthed through an inductance (known as peterson coil).

PLATE NO. 5A

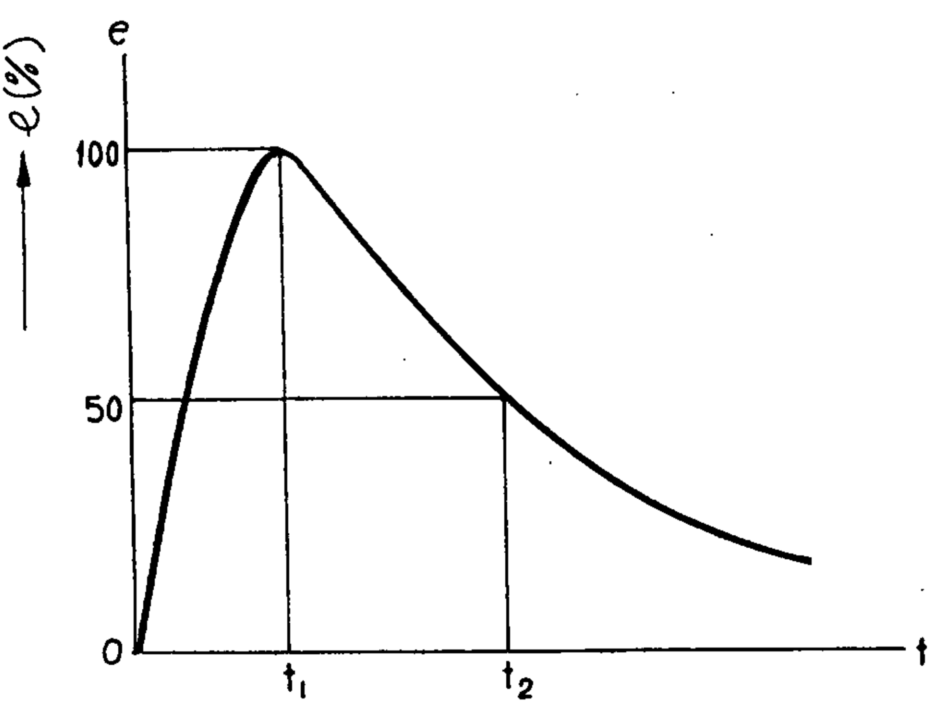


Fig: Nature of Lightning Discharge.

There are two accepted theories of arching earths, in one of which the arc is extenguished at the normal frequency, and in the other at the frequency of oscillation of the line. Let us consider the normal frequency arc extinction theory for a three-phase line.

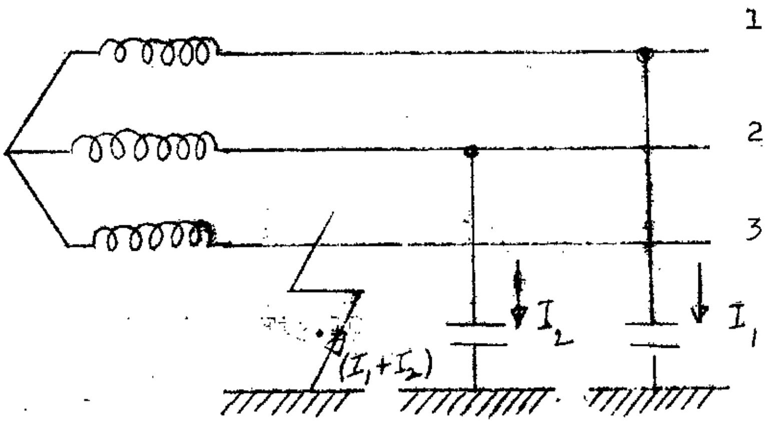


Fig.10 Arching ground in three phase line.

The fig.10 shows a three phase line. Suppose that line 3 arcs to earth when its voltage to neutral is a maximum-E, At this instant line 1 and 2 have voltages +½ E. Before the arching earth occurs the capacitances of the lines cause the neutral to be at or near the earth potential, so that the earthing of line 3 cause a sudden voltage of + E to be applied to lines 1 and 2. The ultimate steady state would then be for the lines 1 and 2 to be at potential 3E/2. But we have shown (refer to Art.4-3-2) that when an emf E is suddenly switched into a circuit of low resistance, the voltage in the circuit oscillates between 0 and 2E with a frequency $1/(2\pi\sqrt{LC})$ (refer equation 9 and 10), where L and C are the inductance and capacitance in the circuit. The voltage of line 1 and 2 will therefore oscillate rapidly between the original value of ½ E and [illegible] = ½ E + 2E = 5E/2. The high frequency oscillation dies out rapidly. The arc is fed through the capacitances of the lines, as shown in Fig.10, and will go out, when the sum of the capacitance currents passes through zero. The capacitance currents lead the voltage by 90^{o}, so that when their sum $I_1 + I_2$ is zero the line voltages are $E_1 = -3E/2$, $E_2 = -3E/2$ and $E_3 = 0$.

If the arc were to remain extenct, the voltages would have to be these values plus E, viz $E_1 = -\frac{1}{2}E$, $E_2 = -\frac{1}{2}E$ and $E_3 = +E$. Thus the faulty line 3 would have a maximum voltage again, and so arc to earth again. In other words, when line 3 arcs to earth the capacitance currents of lines 1 and 2 maintain the arc until the voltage of line 3 attains its oppesition maximum voltage with respect to the neutral. Then at the instant when the capacitance currents would allow the arc to go out, line 3 arcs again to ground. We see that at the instant that the arc is extanct the lines are at potentials $-3E/2$, $-3E/2$ and 0. The charges due to these potentials diffuse rapidly through the system in an oscillatory manner, with the average voltage $1/3\,(-3E/2 - 3E/2 + 0) = -E$ as the mean position. This is equivalent to an insertion of an emf of $\frac{1}{2}E$ in lines 1 and 2, so that an added voltage $+E$ is applied to these lines. When the arc restrikes, lines 1 and 2 acquire potentials of $-5E/2$ plus this new value $-E$, so that the maximum voltage is $+7E/2$. We see therefore that the healthy lines are subjected to a voltage 3½ times the noraml value. As this state can be maintained for a considerable length of time, in a known case 30 minutes, by the continued arching, it is very dangerous.

C H A P T E R- 5

STUDIES WITH THE TRANSIENT ANALYZER

5.1. GENERAL BACK GROUND:

The Network can be energized by five external sources in harmony with the actual power system. In energizing the model system with more than one sources, proper care must be taken, otherwise any two sources may become short circuited through the common ground line.

For this study it was decided to energize the Analyzer at point 13-14 by a 132V souurce obtained from any two phases of a 3-Ø synchronous generator. The Analyzer was utilized to perform the following sets of experiments.

(1) Study of no load voltages and currents .

(2) Study of switching transients for different types of loads.

(3) Study of short circuit transients.

(4) Study of lightning surges by means of square pulses.

(5) Study of resonance phenomena during lightning surges by initiating square pulses of varying repititionarate.

5.2. EXPERIMENTAL SET UP:

For observing the voltage and current transients during switching operations and fault conditions the exciting source (the three phase synchronous generator of the AEG generalized machine set) was run at a speed of 1500 rpm which corresponded to a system frequency of 50 Hz. The generated voltage was adjusted to 132V by varying the field rheostat and was fed at the terminals of sections 13-14 of the Analyzer.

Before the traisient studies, the no load voltages at different points of the system was measured. Then the transient voltages and currents at different sections of the Analyzer for various loads and fault conditions were observed on the screen of a storage oscilloscope.

A potential divider arrangement in the ratio of 1:5 output (i.e. output from 2 k.ohms. was fed to the scope while the system voltage was fed across 10 k.ohms potentiometer). This arrangement facilitated direct observation of voltage transients on the screen. This was essential as only 60V could be observed directly on the screen, where as the system voltage raised upto 300V as obtained by the no load study.

An ammeter (0-2.5-5A range) having low resistance was connected in series at different sections of the Analyzer. This arrangement provided an adequate voltage drop for direct observations of currents on the screen of the oscilloscope as well.

For permanent records the voltage and current transients were stored on the oscilloscope screen and photographs were taken by an oscilloscope Camera.

The experimental set up for these studies are shown in the photographs of plate no.5(Page 61). While the plate no.6(page no.62) shows the close up view of the Transient Analyzer together with the different apparatus of the laboratory test set up.

5.3. NO LOAD STUDIES:

Before the studies of switching surges for different types of loads, the no load voltages and the charging current at different sections of the system was measured. For measurement a high resistance voltmeter and a sensitive ammeter were used. The open circuit voltage and the charging current is recorded in Table-6 (page 63).

PLATE NO.5

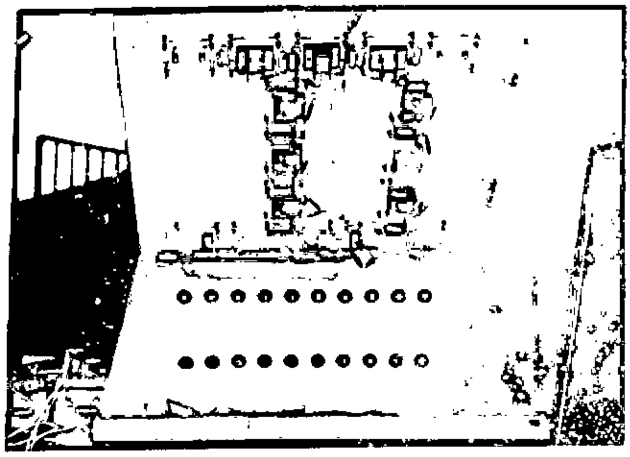
THE EXPERIMENTAL SET UP.

Note: The photograph shows the transient analyzer (1), exciting sources- the synchronous generator (2) , the square wave generator (3), the storage oscilloscope(4) and other equipments and accessories of the experimental set up.

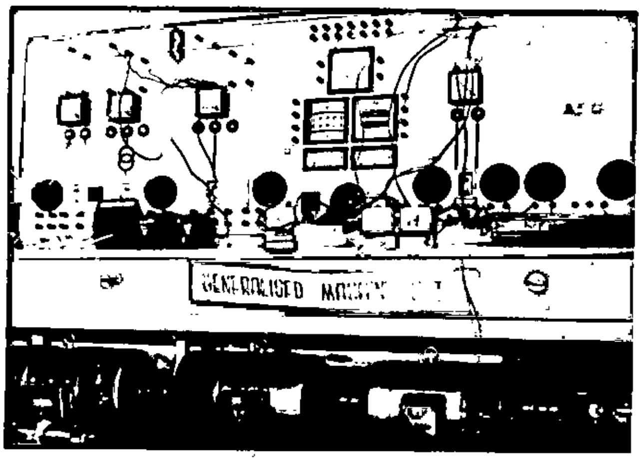
PLATE NO.6

Close up view ofthe Analyzer and the experimental set up.

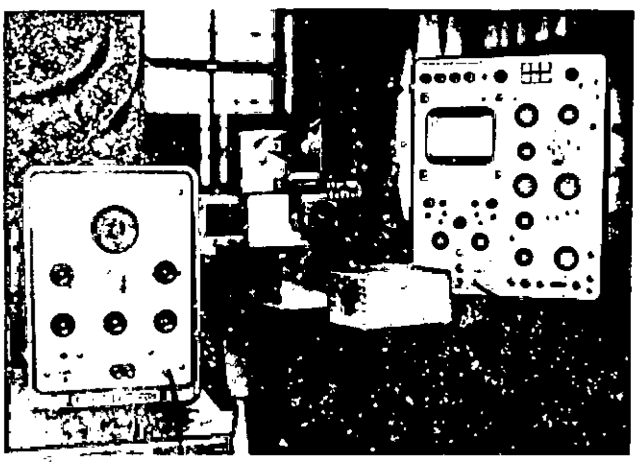
(a) The Transient Analyzer



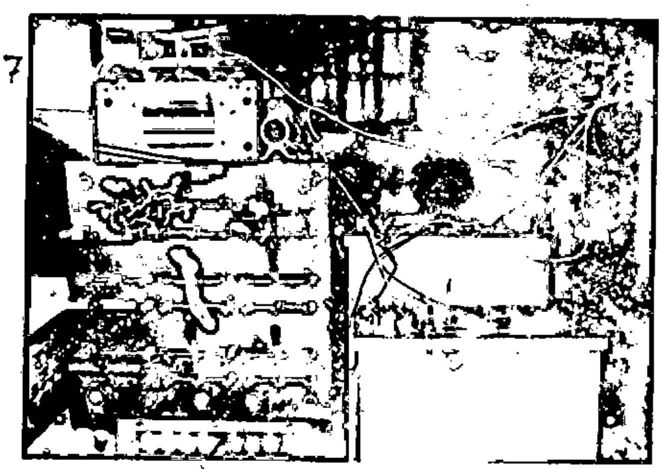
(b) Inside view of the Analyzer.



(c) Synchronous generator(2) and its primemover-
D.C. shunt motor(3). Ammeters and voltmeters(11)



(d) The square wave generator(4), storage oscilloscope (5) and the oscilloscope camera(6)



(e) Resistive loads(8), Inductive loads (9), Capacitive loads(7) & potential divider(10)

TABLE-6

NO LOAD VOLTAGES AND CHARGING CURRENTS

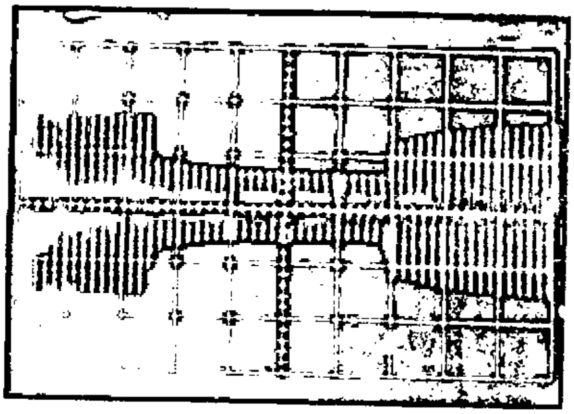
No. of observation	Exciting voltage at point 13-14 (volts)	No load voltage			Distance from the exciting source (miles)	Charging current	
		measured at points	Actual value (volts)	Per unit value base 132V		Actual value (Amp.)	Per unit value base 0.42A
1	132	(12-13)	135	1.023	6	0.42	1.0
2	132	(11-12)	145	1.090	30	0.38	0.905
3	132	(10-11)	170	1.290	90	0.34	0.808
4	132	(9-10)	185	1.400	120	0.30	0.715
5	132	(9-3)	205	1.555	170	0.22	0.524
6	132	(3-4)	215	1.63	200	0.20	0.476
7	132	(4-5)	220	1.67	225	0.12	0.286
8	132	(5-6)	225	1.705	255	Negligible and the value is always less than 0.1A	
9	132	(8, Far-end)	230	1.74	325		
10	132	(1-2)	210	1.59	190		

Note: Here 0.42 Amp. is taken as 1 p.u. of current for the sake of comparison only.

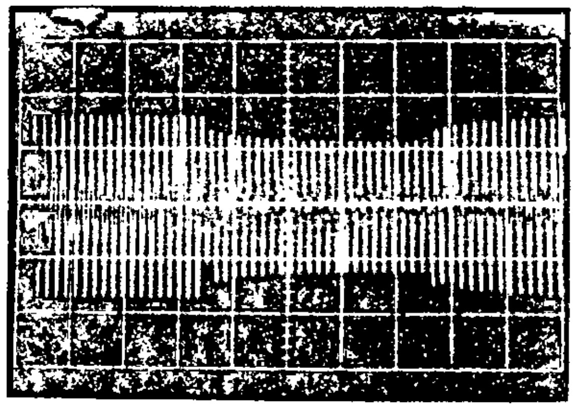
PLATE NO.7

5.3.1 STUDY OF SWITCHING SURGES FOR RESISTIVE LOADS.

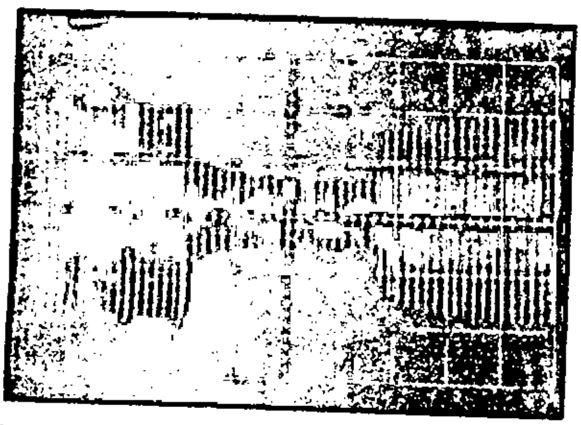
1. Voltage Transients for resistive loads (R= 80 ohm.) applied (A) at point 11-12 (30 miles) (figure a,b,c) and (B) at point 9-10 (120 miles) figure d,e,f.).



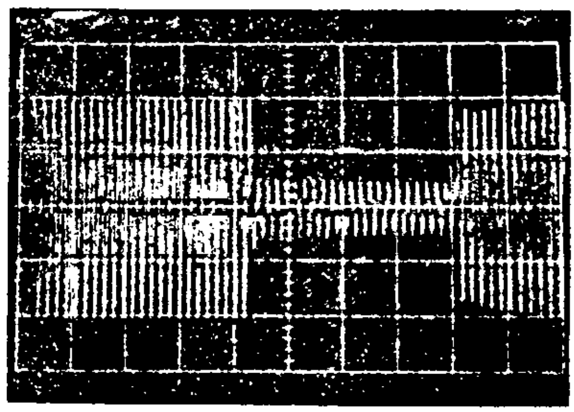
(a) 5 V/cm x 5 and 0-.1 sec/cum at point 12-13(6 miles).



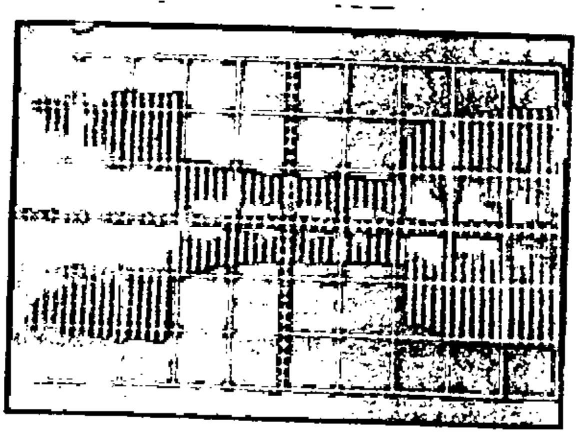
(d) 5 V/cm x 5 and 0.1 sec/cm. at point, 12-13 (6 miles).



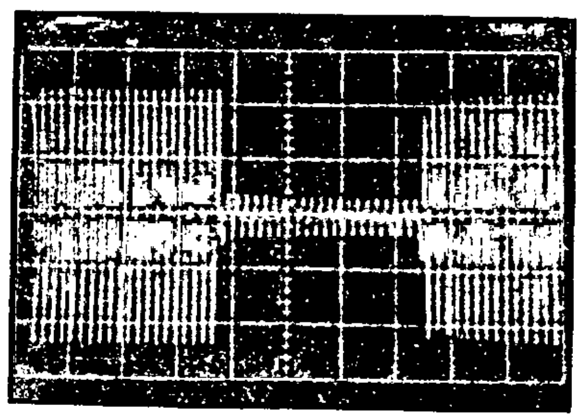
(b) 5 V/cm.x5 and 0.1 sec/cm. at point 10-11 (90 miles)



(e) 5 V/cm x 5 and 0.1 sec/cm. at point 10-11 (90 miles)



(c) 5 V/cm x 5 and 0.1 sec/cm. at point 3-4 (200 miles)



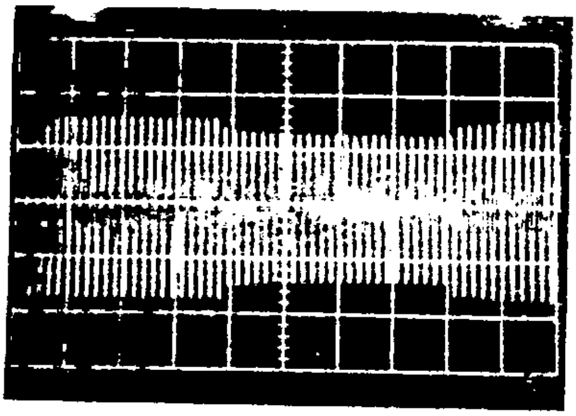
(f) 5 V/cm x 5 and 0.1 sec/cm. at point 3-4(200 miles).

Note: The figures within bracket show the distance in miles from the 132V source.

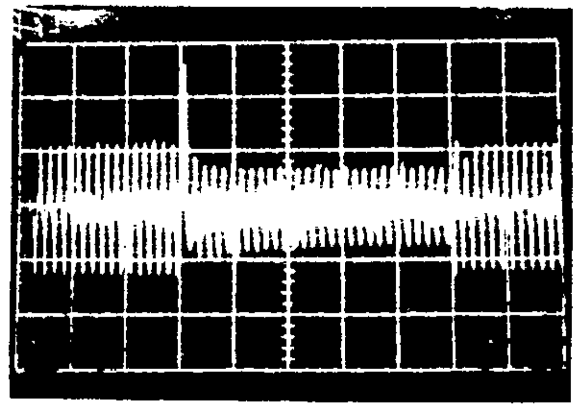
PHOTO. No. [illegible]

5.3 STUDY OF SWITCHING [illegible]

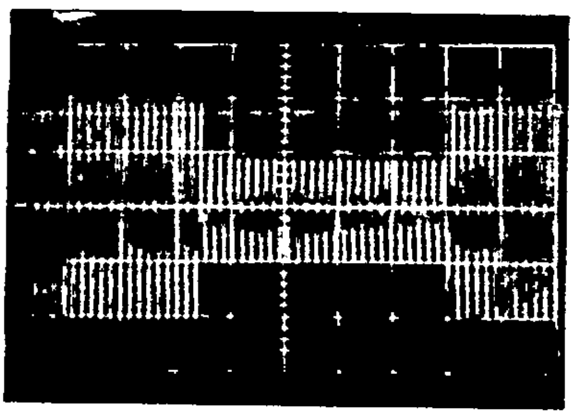
[illegible] Voltage Transients for [illegible] (R = [illegible]0 ohms.) applied at point 4-5 [illegible]5 miles, (Fig. a,b,c) and 2 [illegible] current transients for the same fig. (d,e,f).



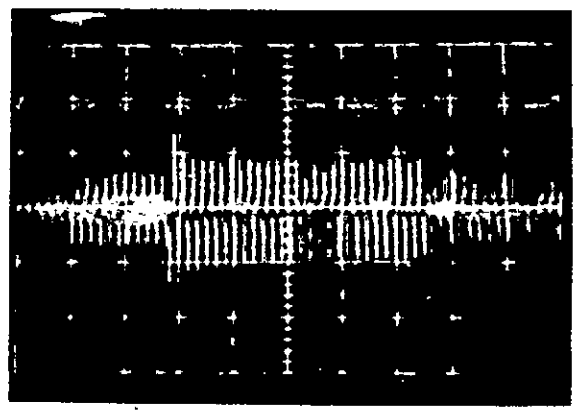
(a) 20 V/cm x 5 and 0.1 sec/cm at point 12-13 (6 miles)



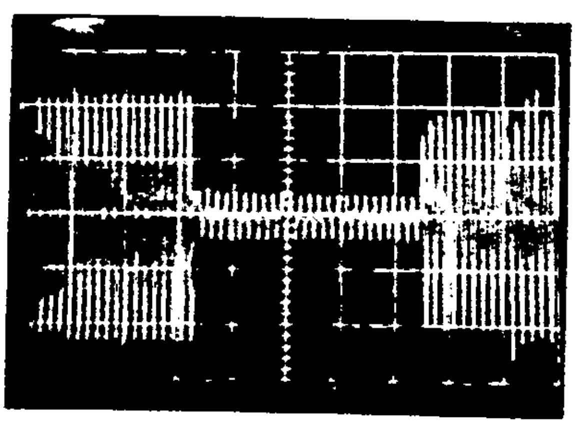
(d) 0.05 v/cm and 0.1 sec/cm. at point 12-13 (6 miles).



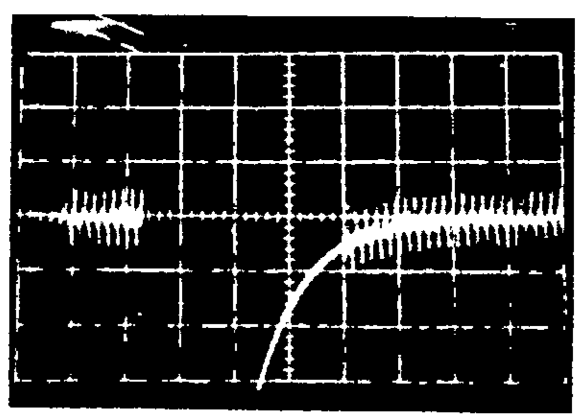
(b) 20 V/cm x 5 and 0.1 sec/cm. at point 10-11 (90 miles).



(e) 0.05v/cm. and 0.1 sec/cm. at point 3-4 (200 miles).



(c) 20V/cm x 5 and 0.1 sec/cm. at point (3-4) (200 miles).

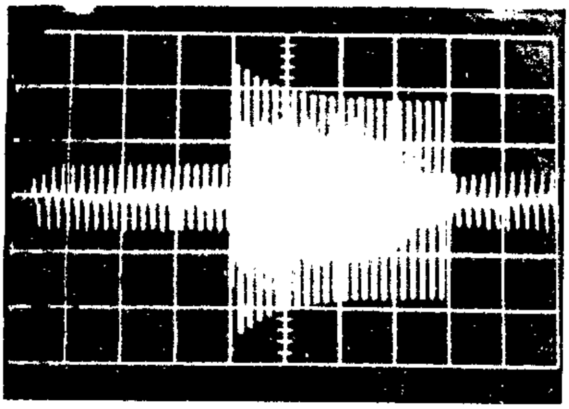


(f) 0.05V/cm. and 0.1 sec/cm. at point 4-5 (load point)

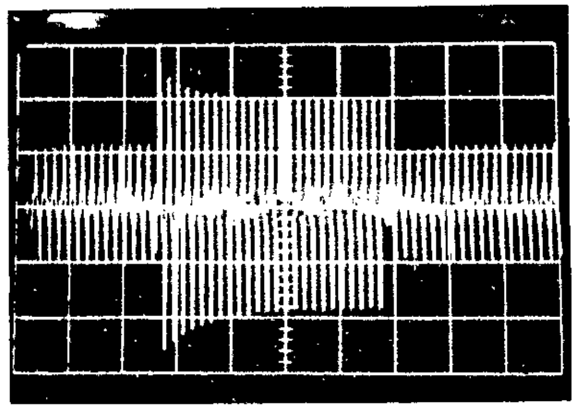
PLATE NO.9

5.3.2 STUDY OF SWITCHING SURGES FOR RESISTIVE LOADS

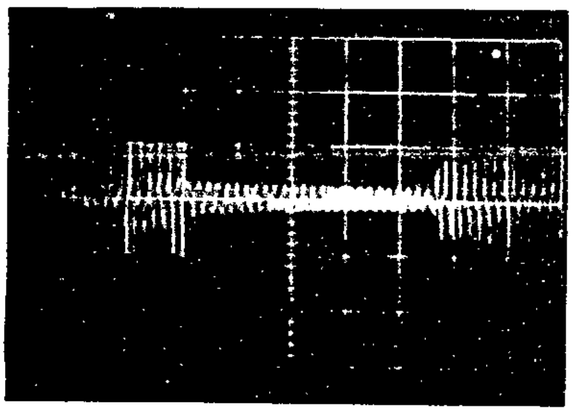
Current Transients for resistive loads (R = 80 ohms.) applied(A) at point 11-12 (30 miles) (figure a,b,) and (B) at point 9-10 (120 miles (figure c,d,e)



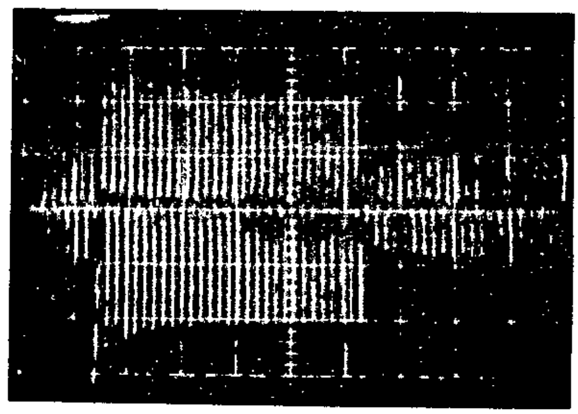
(a) 0.1V/cm and 0.1 sec/cm.
at point 12-13 (6 miles)



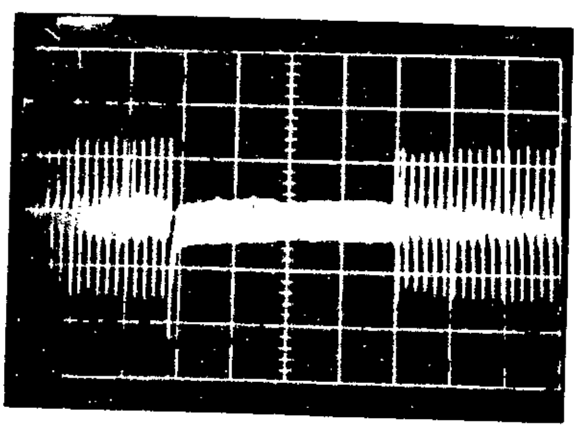
(c) 0.05V/cm and 0.1 sec/cm.
at point 12-13(6 miles).



(b) 0.05 V/cm. and 0.1 sec/cm.
at point 9-10 (120 miles)



(d) 0.05v/cm and 0.1 sec/cm.
at point 9-10 (load point).



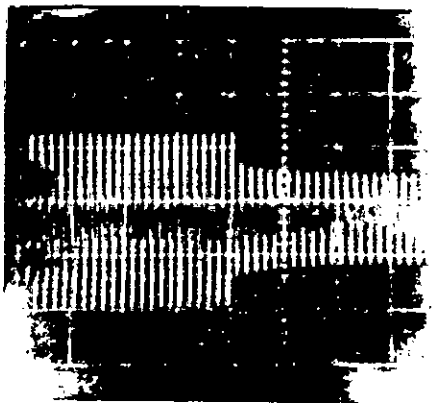
(e) 0.05V/cm and 0.1 sec./cm.
at 3-4 (200 miles), (beyond
load point.)

Note: The distance shown is from the 132V source at point 13-14.

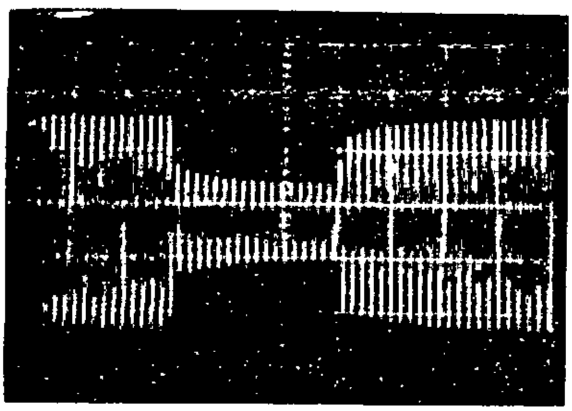
PLATE NO. 10.

5.4.1. SWITCHING SURGES FOR INDUCTIVE LOADS.

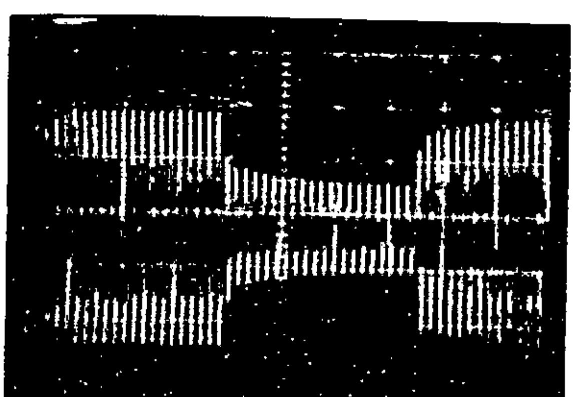
1. Voltage Transients for Inductive loads CX_2 = 40 ohms, 24 ohms) applied (A) at point 11-12 (30 miles) (figure a,b,c) and (B) at point 9-10 (120 miles) (figure d,e,f).



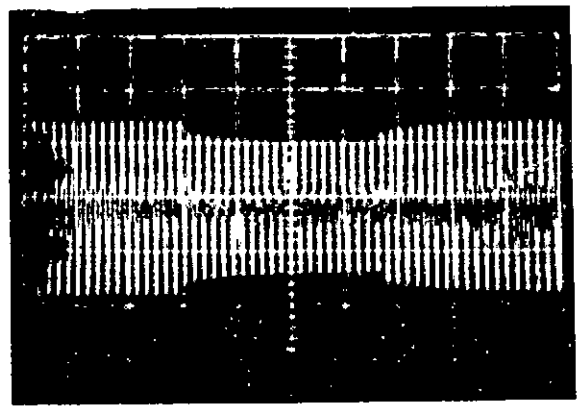
(a) 20v/cm x 5 and 0.1 sec/cm
at point 12-13 (6 miles)



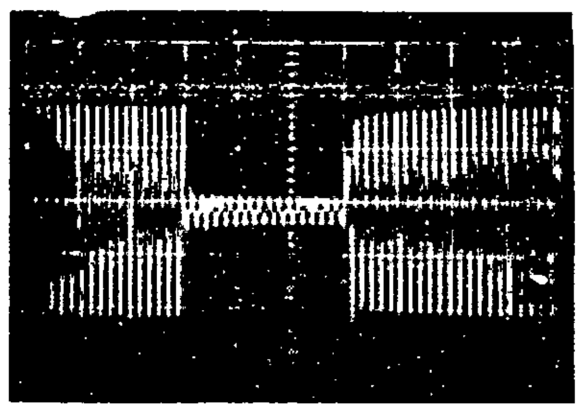
(b) 20 v/cm x 5 and 0.1 sec/cm.
at point 9-10 (120 miles)



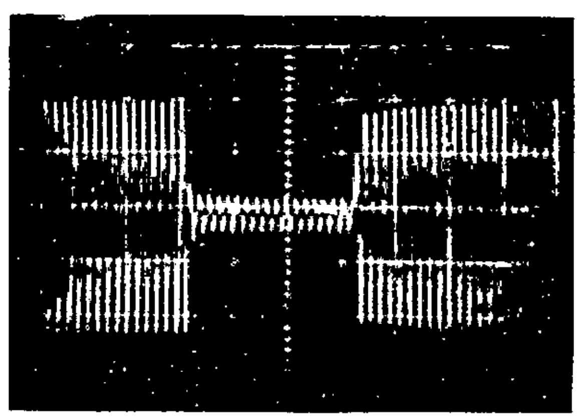
(c) 20v/cm x 5 and 0.1 sec/cm.
at point 4-5 (225 miles)



(d) 20 v/cm x 5 and 0.1 sec/cm.
at point 12-13 (6 miles).



(e) 20v/cm x5 and 0.1 sec/cm.
at point 9-10 (load point)

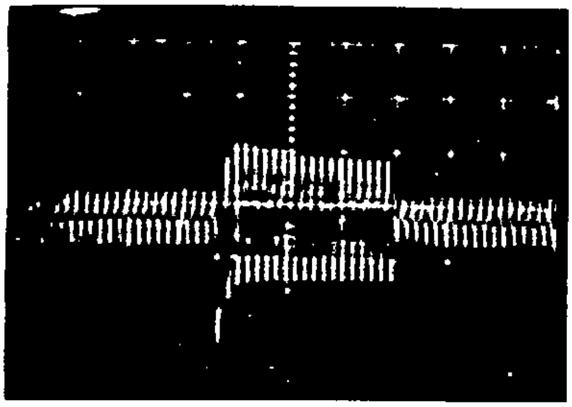


(f) 20 v/cm x 5 and 0.1 sec/cm.
at point 4-5 (225 miles).

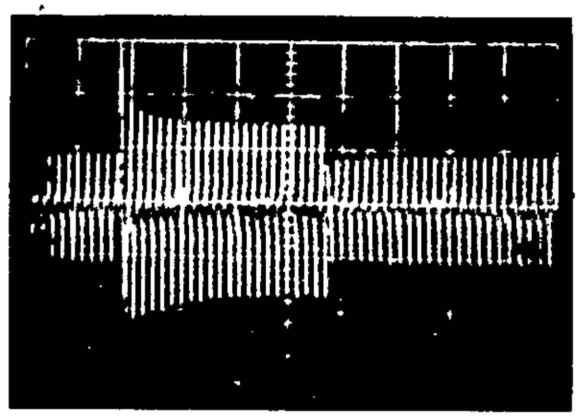
PLATE NO. 11

5.4.2. STUDY OF SWITCHING SURGES FOR INDUCTIVE LOADS.

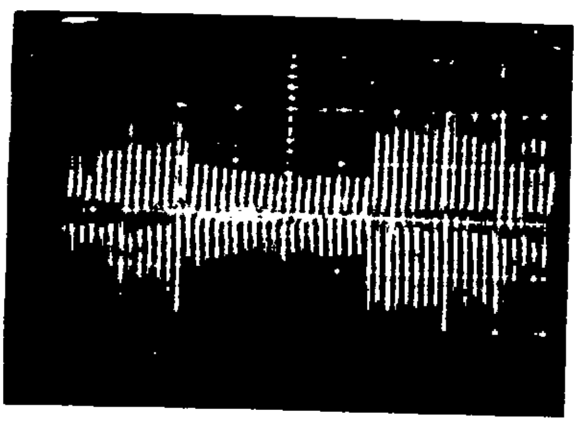
Current transients for inductive loads (X_L = 40 ohms, 24 ohms) applied (A) at point 11-12 (30 miles) (Figure a,b) and (B) at point 9-10 (120 miles) (figure c,d,e).



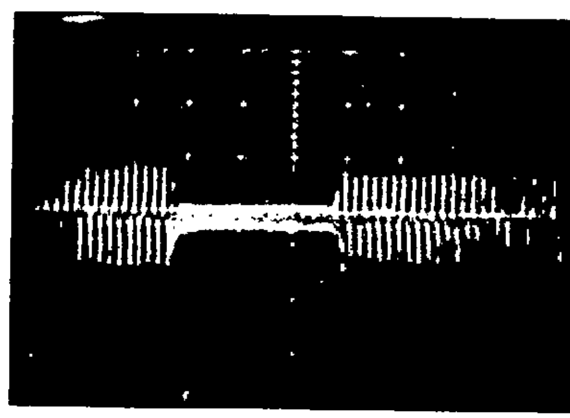
(a) 0.1V/cm and 0.1 sec/cm at at point (12-13) (6 miles).



(c) 0.05v/cm and 0.1 sec/cm at point 12-13 (6 miles).



(b) 0.02v/cm/ and 0.1 sec/cm at point 9-10 (120 miles) (beyond load point)



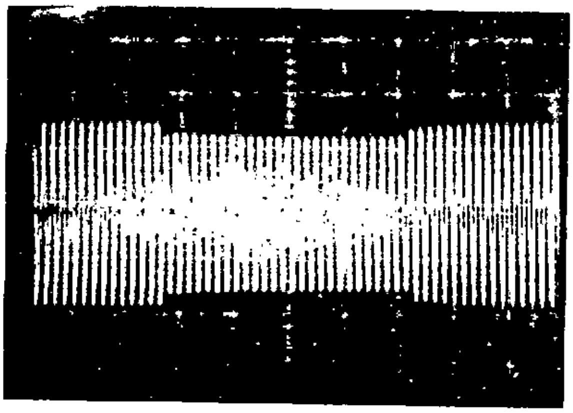
(d) 0.02v/cm and 0.1 sec/cm. at point 9-10(load point).

Note: At point 11-12 the load (X_B = 40 ohms) and at point 9-10 to the load (X_L = 24 ohms) were applied.

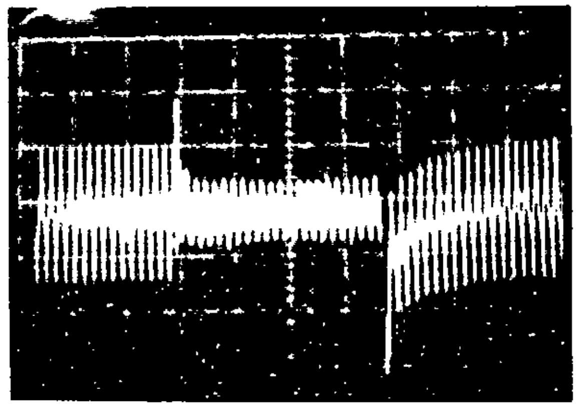
PLATE 12

5.4 STUDY OF SWITCHING SURGES FOR INDUCTIVE LOADS.

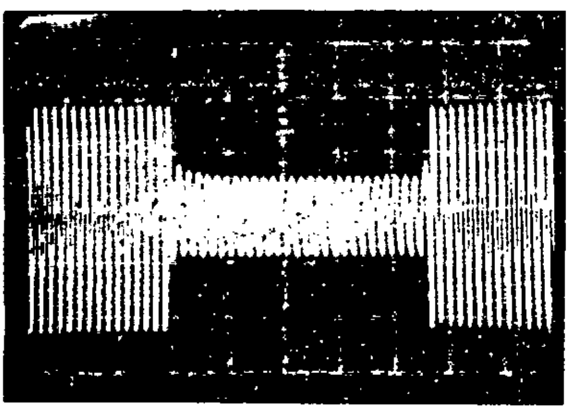
IC. Voltage transients for inductive loads (X_L = 60 ohms) at point 4.5 (225 miles) (figure a,b,c) and 2.C. current transients for the same (figure d,e,f).



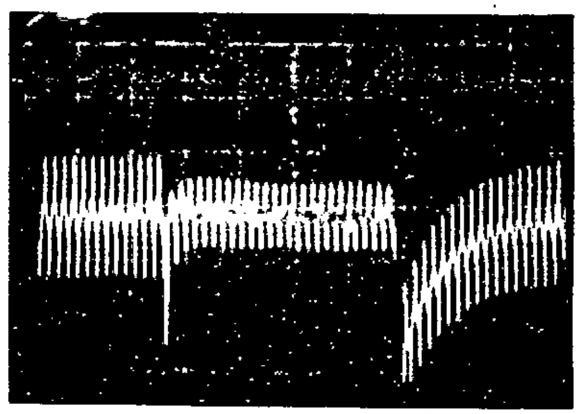
(a) 20v/cm x5 and 0.1 sec/cm. at point 12-13 (6 miles)



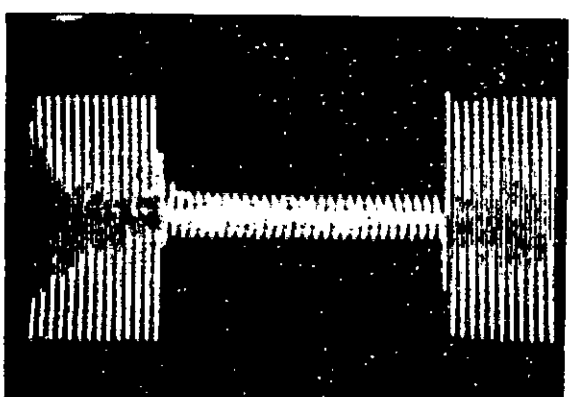
(d) 0.05v/cm and 0.1 sec/cm. at point 12-13 (6 miles).



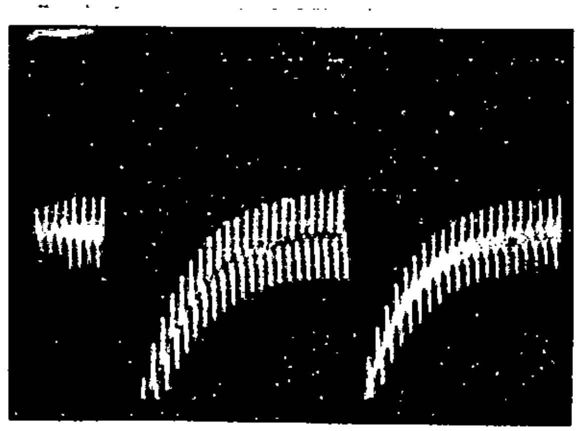
(b) 20v/cm x 5 and 0.1 sec/cm. at point 9-10 (120 miles)



(e) 0.05v/cm and 0.1 sec/cm at point 9-10 (120 miles)



(c) 20 v/cm x 5 and 0.1 sec/cm. at point 5-6 (255 miles) and beyond load point).



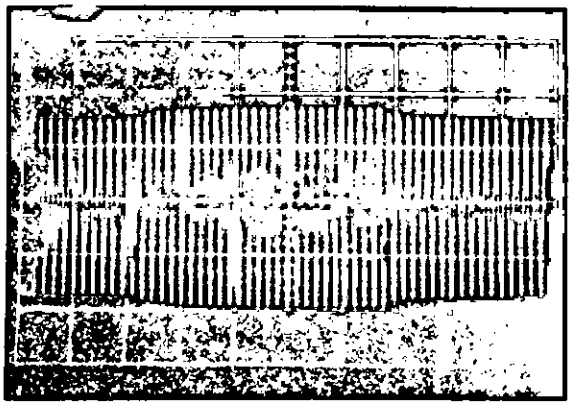
(f) 0.05v/cm and 0.1 sec/cm. at point 3-4 (200 miles).

PLATE NO. 13

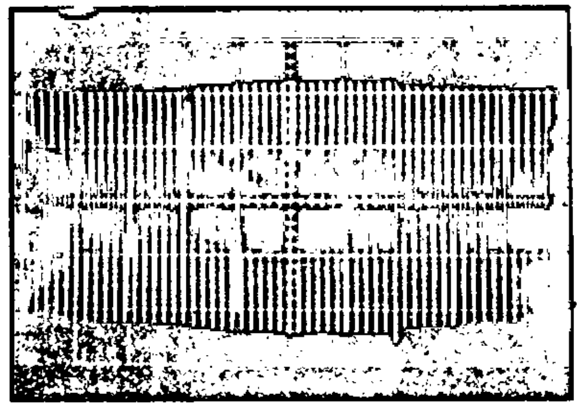
5.5 STUDY OF SWITCHING SURGES FOR CAPACITIVE LOADS.

1. Voltage Transients for capacitive loads (c- 10 MFD) applied (A) at point 11-12 (30 miles) (fig. a, b) and (B) at point 9-10 (120 miles) (Fig.c,d).

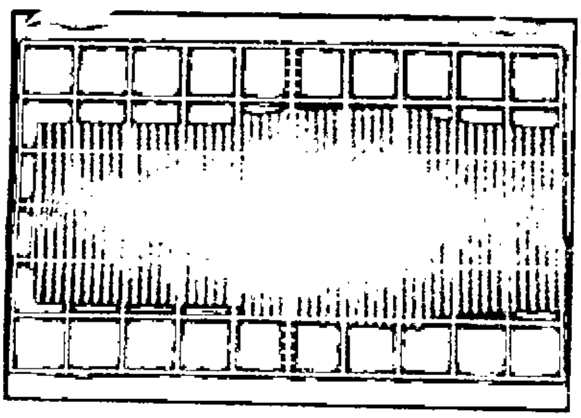
2. Current transients for the same when applied at point (9-10) (fig.e,f).



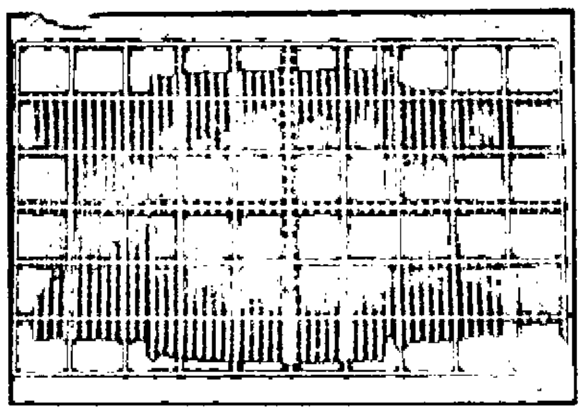
(a) 20 v/cm x 5 and 0.1 sec/cm.
at point 12.13 (6 miles)



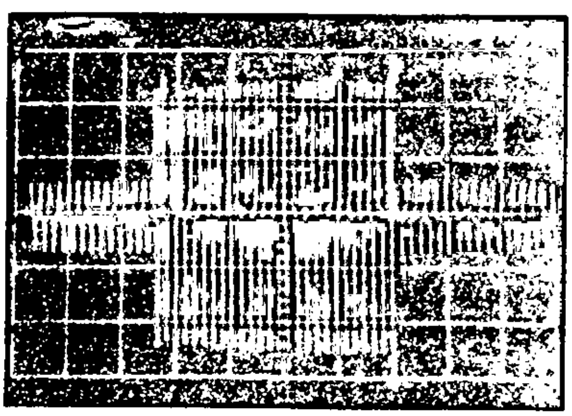
(b) 20 v/cm x 5 and 0.1 sec/cm.
at point 3-9 (170 miles).



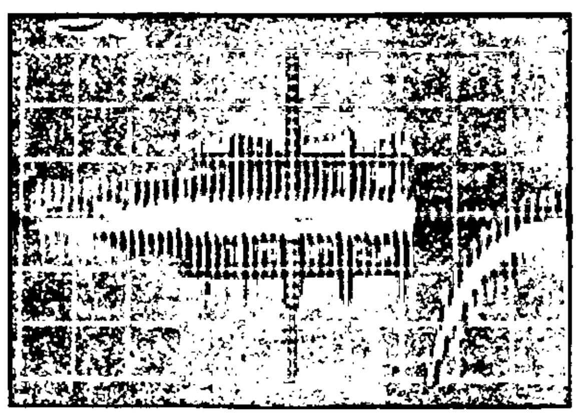
(c) 20V/cm x 5 and 0.1 sec/cm
at point 12-13 (6 miles).



(d) 20V/cm x 5 and 0.1 sec/cm.
at point 3-4 (200 miles).



(e) 0.IV/cm. and 0.1 sec/cm.
at point 12-13(6 miles)

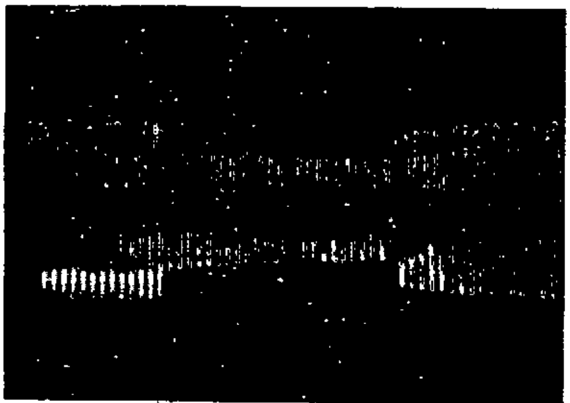


(f) 0.05 V/cm and 0.1 sec/cm
at point 3-4 (200 miles).

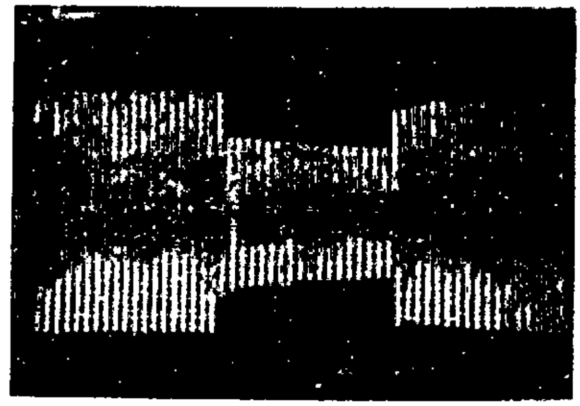
PLATE NO.14

5.6 STUDY OF SWITCHING TRANSIENTS FOR R-L LOADS.

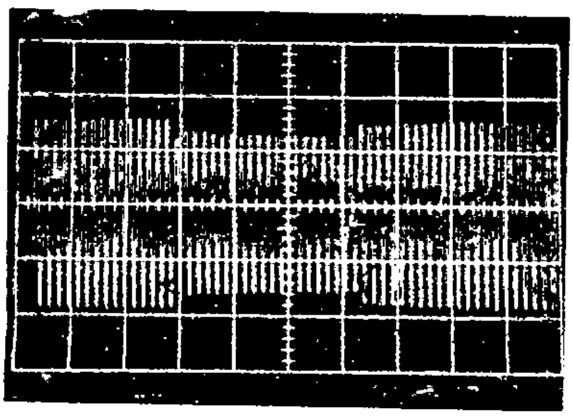
1. Voltage transients for R-L loads (R-80 ohms, X_L = 60 ohms) applied (A) at point 11-12 (30 miles) (figure a,b) and (B) at point 3-9 (170 miles) (fig.c,d) and (C) at point 4-5 (225 miles) (fig.e,f).



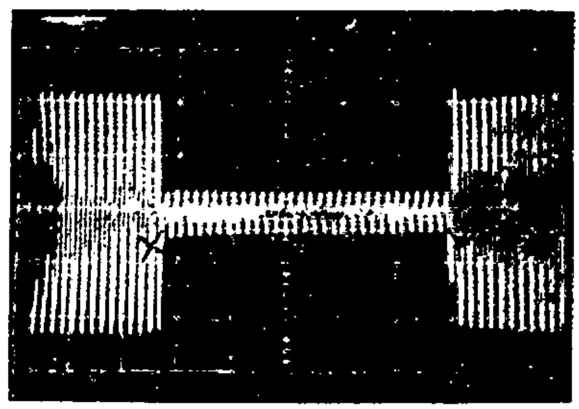
(a) 20v/cm x 5 and 0.1 sec/cm.
at point 12-13 (6 miles)



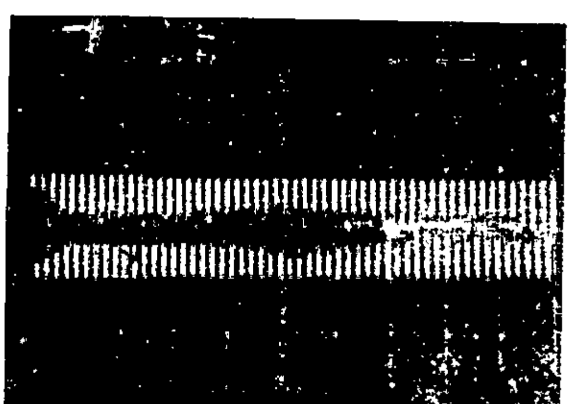
(b) 20 v/cm x 5 and 0.1 sec/cm.
at point 4-5 (225 miles).



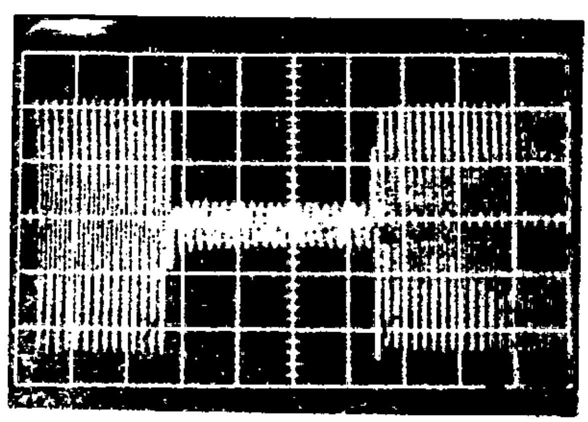
(c) 20V/cm x 5 and 0.1 sec/cm.
at point 12-13 (6 miles)



(d) 20 v/cm x 5 and 0.1 sec/cm.
at point 4-5 (225 miles).



(e) 20v/cm x 5 and 0.1 sec/cm.
at point 12-13 (6 miles)



(f) 20V/cm x 5 and 0.1 sec./cm.
at point 3-4 (200 miles)

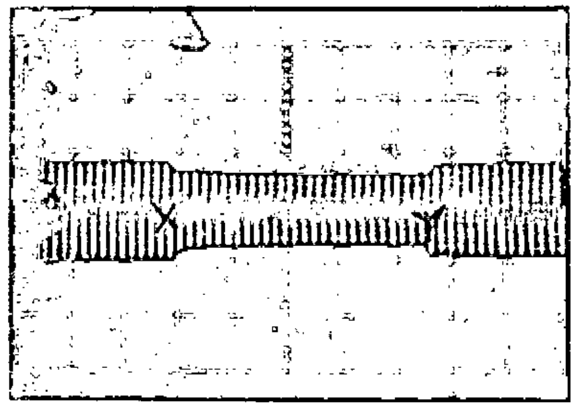
Note: At point 3-9, the R-L load is R = 60 ohms, X_L = 40 ohms)
The distance in miles within bracket is from the 132v source.

PLATE NO. 15

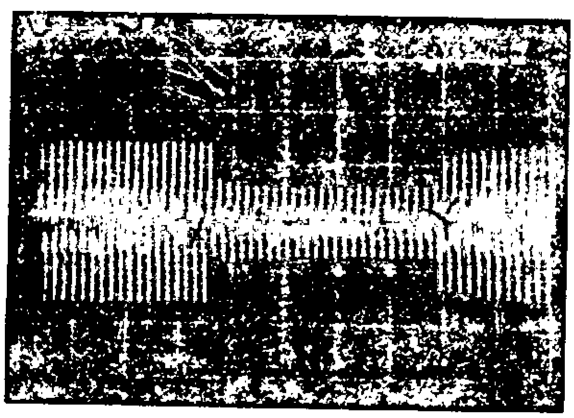
5.6 SWITCHING TRANSIENTS FOR R-L LOADS.

1.D. Voltage Transients for Double R-L loads (R = 60 ohms, X_L = 40 ohms) at point 3-9 (170 miles) fixed and R-L load (R = 80 ohms, X_L = 60 ohms) at point 11-12 (30 miles) switched. (fig.a,b,c). 2A. Current Transients for R-L loads (R = 80 ohms, X_L = 60 ohms) applied at point 11-12 (30 miles) (fig.d,e).

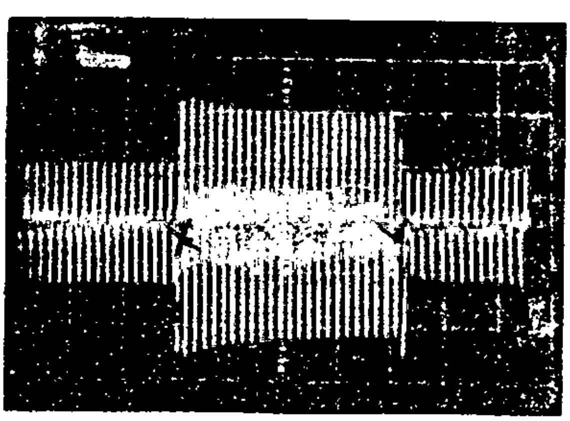
(a) 20 V/cm. x 5 and 0.1 sec/cm. at point 12-13 (6 miles).



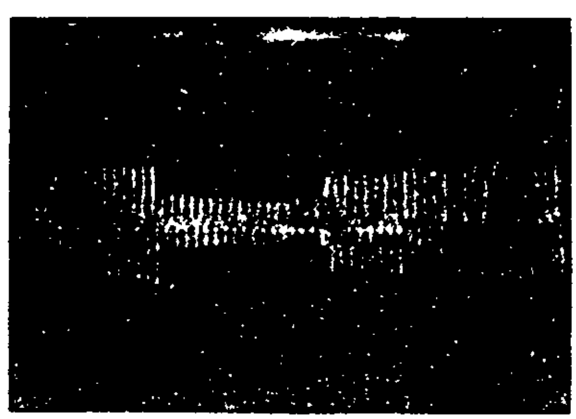
(b) 20v/cm x 5 and 0.1 sec/cm. at point 10-11(90 miles).



(c) 5V/cm x5 and 0.1 sec/cm. at point 4-5 (225 miles)



(d) 0.05v/cm and 0.1 sec/cm. at point 12-13 (6 miles)

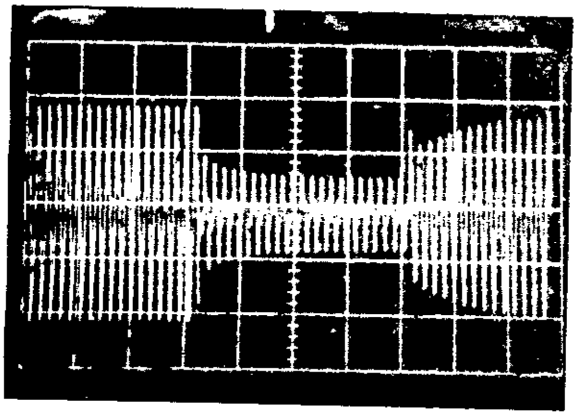


(e) 0.05v/cm. and 0.1 sec./cm at point 10-11 (90 miles).

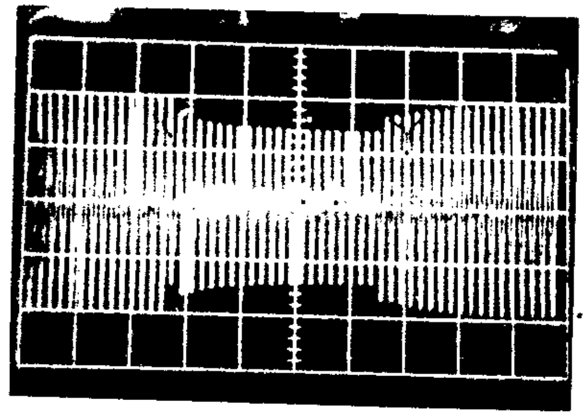
PLATE NO. 16

5.7 STUDY OF SHORT CIRCUIT TRANSIENTS.

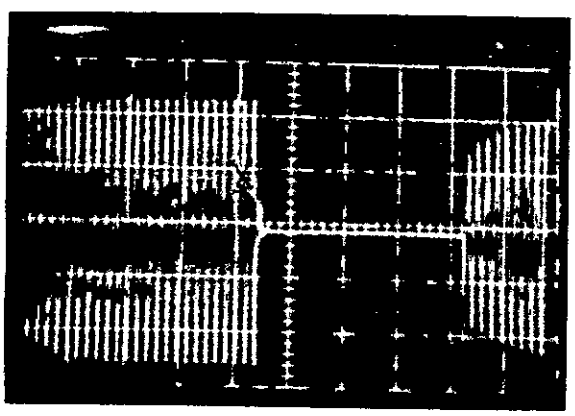
1. Voltage Transients for short circuits.
(A) At point 11-12 (30 miles) (figure a,b) and
(B) at point 9-10(120 miles) (figure c,d,e).



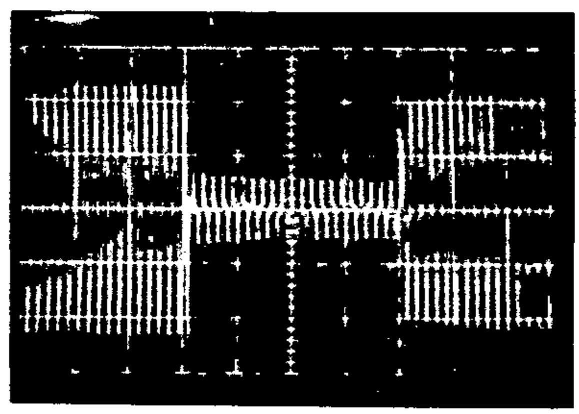
(a) 20V/cm x 5 and 0.1 sec/cm.
at point 12-12 (6 miles).



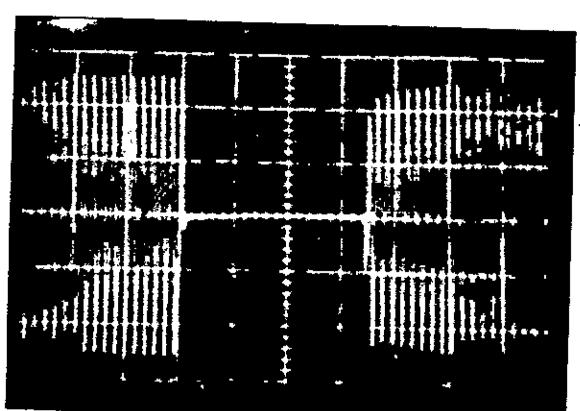
(c) 20V/cmx5 and 0.1 sec/cm.
at point 12-13 (6 miles).



(b) 20V/cm x 5 and 0.1 sec./cm.
at point 9-10 (20 miles).



(d) 20v/cm x 5 and 0.1 sec/cm.
at point 10-11(90miles).

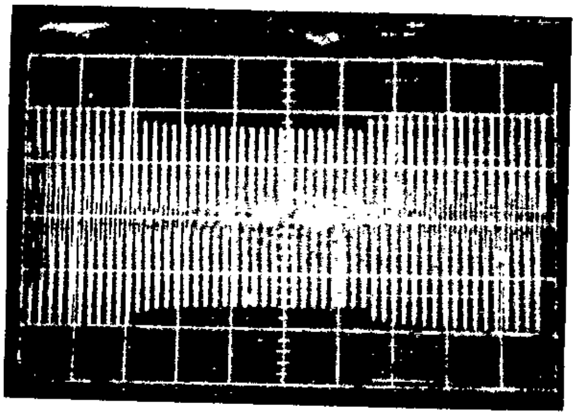


(e) 20V/cm x 5 and 0.1 sec/cm.
at point 3-9(170 miles).

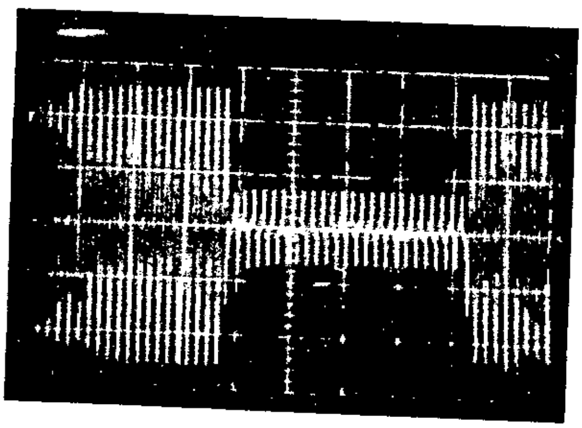
PLATE NO. 17

5.7 STUDY OF SHORT CIRCUIT TRANSIENTS

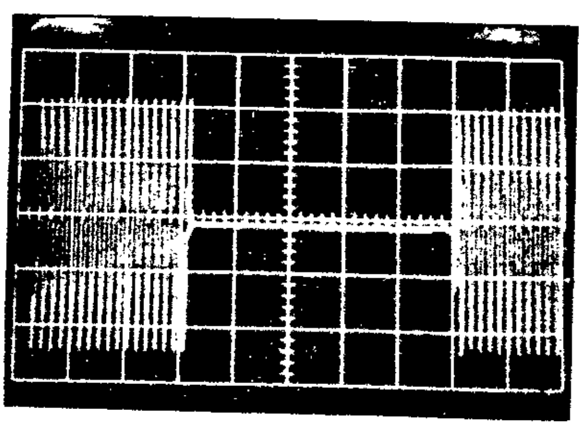
1C. Voltage Transients for short circuit at point 4-5(225 miles) .



(a) 20V/cm x 5 and 0.1 sec./cm
at point 12-13 (6 miles)



(b) 20V/cm x 5 and 0.1 sec/cm
at point 3-9 (170 miles).



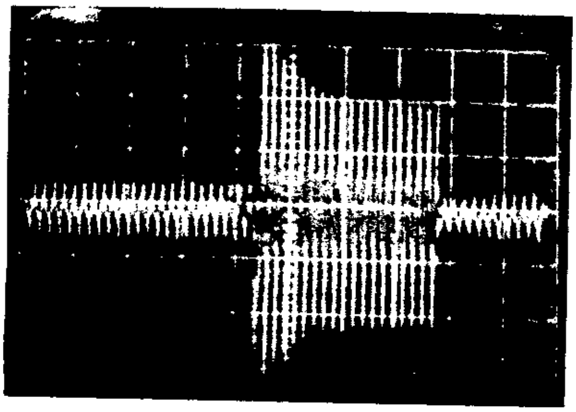
(c) 20V/cm x 5 and 0.1 sec/cm.
at point 5-6 (255 miles).

Note: The distance is from 132V source at point 13-14.

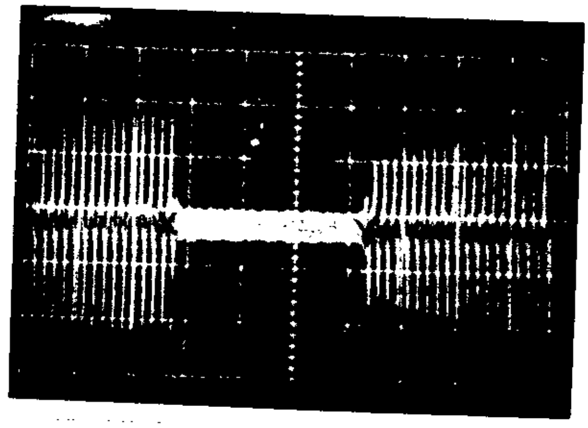
PLATE NO. 18

5.7. STUDY OF SHORT CIRCUIT TRANSIENTS

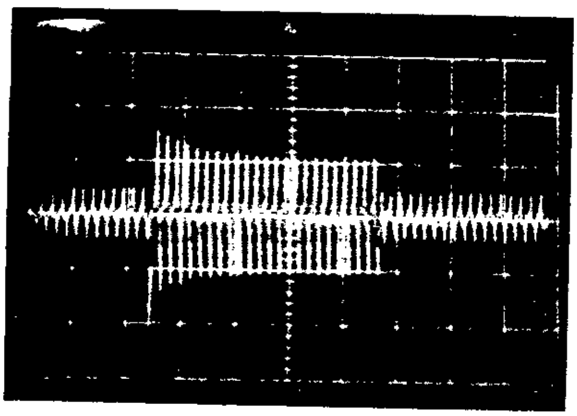
2. Current Transients for sudden short circuit (A) at point 11-12 (30 miles(fig. a,b) and (B) at point 9-10(120 miles) (Fig.c,d) & (C) at point 4-5 (225 miles) (fig. e,f).



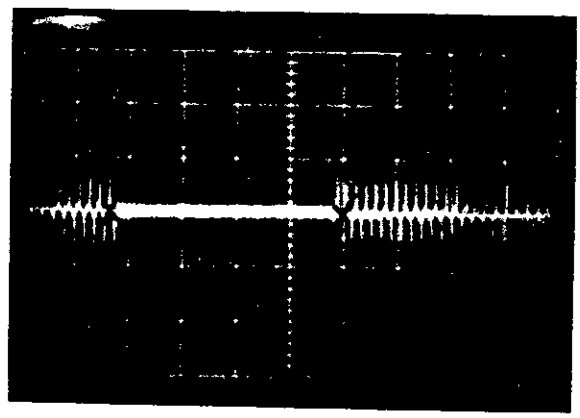
(a) O.IV/cm and 0.1 sec./cm. at point 12-13 (6 miles).



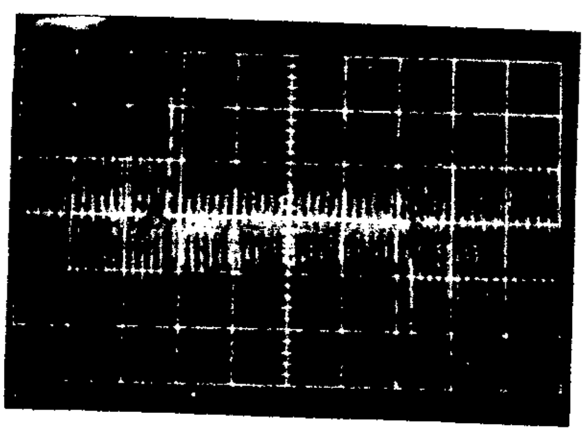
(b) O-IV/cm and 0.1 sec/cm. at point 9-10 (120 miles).



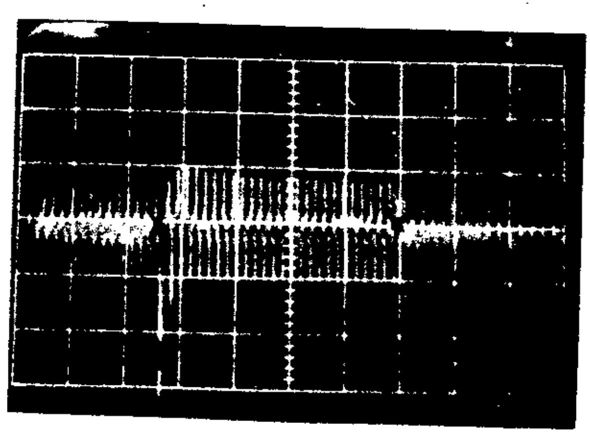
(c) 0.1V/cm. and 0.1 sec/cm. at point 12-13 (6 miles).



(d) 0.05 V/cm and 0.1 sec/cm. at point 3-9 (170 miles).



(e) 0.05V/cm and 0.1 sec/cm at point 12-13



(f) 0.05V/cm and 0.1 sec/cm. at point 3-9 (200 miles).

5.8.1. IMPULSE WAVES (LIGHTNING SURGES) AND RESONANCE PHENOMENA

For stydign lightning surges and associated resonance phenomena a square pulse of maximum amplitude of 7V peak to peak having an input impedance of 60 ohms. was applied from the square wave generator. The variation of the width of the pulse was made as required by the "symmetrical switch". The pulse repitation rate was varied from 20 pps to 60 pps. For these studies the 132V exciting source at point 13-14 of the Analyzer was not energized. Instead like the usual practice, was replaced by a 0.8 pf. R-L (R = 80 ohms, X_L = 60 ohms.) load.

Only the voltage surges were observed on the oscilloscope screen and photographs taken by the oscilloscope-camera as was done during switching surges. The lightning surges were observed for the following three conditions.

Condition-1: No load connected to the system except the simulated disturbance.

Condition-2: 132V sourde at point 13-14 replaced by a 0.8 pf (R = 80 ohms., X_L = 60 ohms) load.

Condition-3: 132V source replaced at point 13-14 by a 0.8 pf. load together with another 0.85 p.f.(R =100 ohms, X_L = 60 ohms) load at point 3-9.

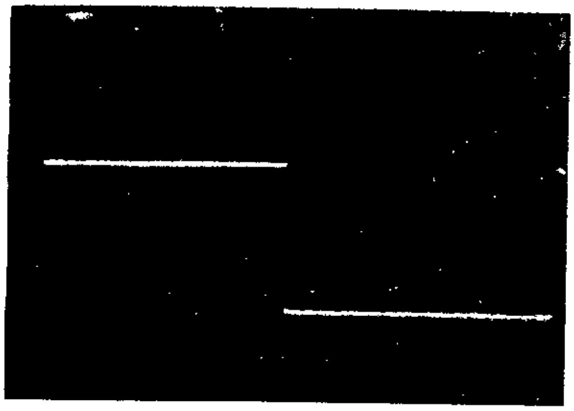
For studying resonance phenomena, the oscillogram at 13-14 for no load condition was recorded when square pulse was applied at point 9-10. Then the repitation rate of the input pulse at point 9-10 was gradually increased in steps from 60 pps upto 500 pps, and simultaneously the oscillograms at point 13-14 were recorded.

PLATE- 19

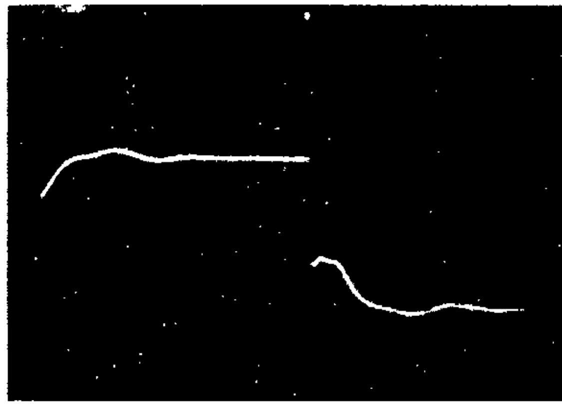
5.8 STUDY OF LIGHTNING SURGES FOR DISTURBANCE AT POINT 9-10.

1.A. Input (voltage) pulses (7 V peak to peak and 60 pps) (figure a,b)

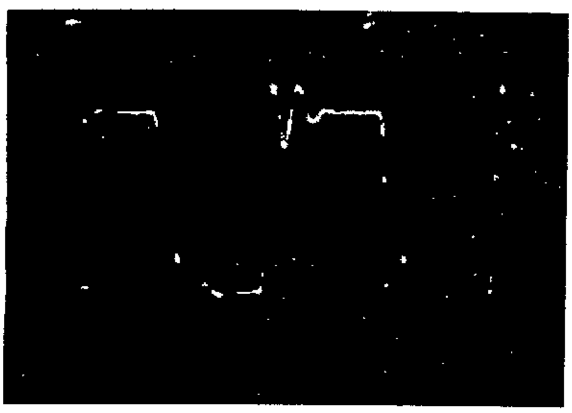
1.B Output (voltage) pulses at point 11-12 (90 miles from the disturbance) (Figure c,d,e)



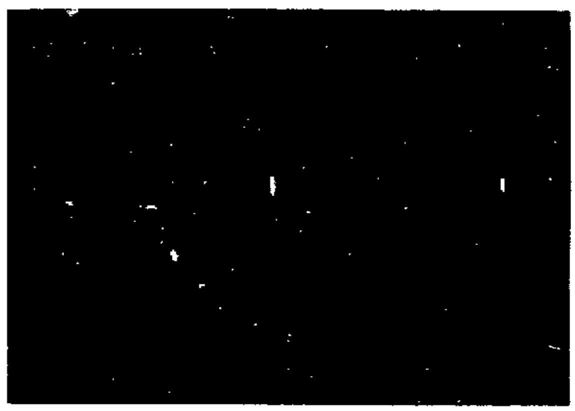
(a) 2V/cm and 2 m sec/ cm input pulse before injection



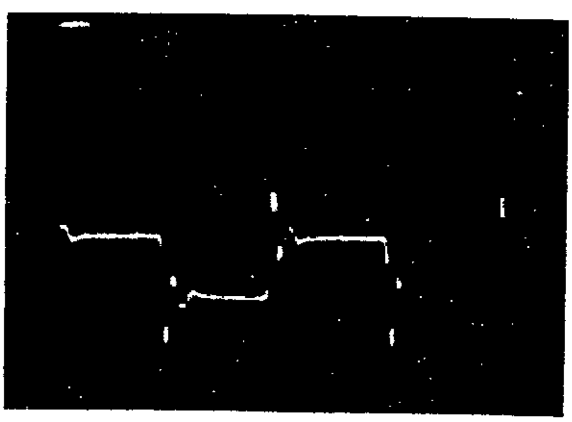
(b) 2v/cm and 2 m sec/cm Input pulse after injection at point 9-10.



(c) 2v/cm and 5 m sec/cm input pulse at point 11-12 for condition 1 (no-load)



(d) 2v/cm and 5 m sec/cm output pulse at point 11-12 for condition 2 (132v source at 13-14 replaced by 0.8 p.f. load).

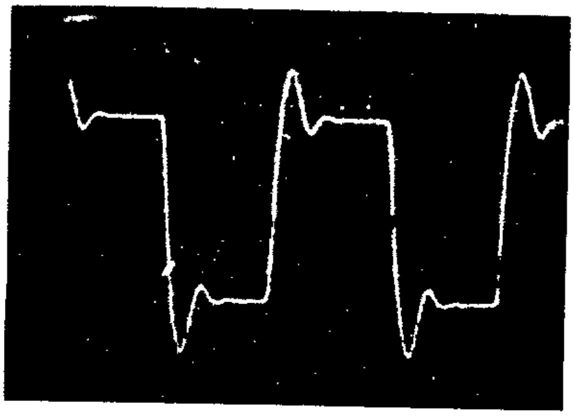


(e) 2v/cm and 5 m sec/cm. output pulse at point 11_12 for condition-3 (condition 2 and 0.85 p.f.load at

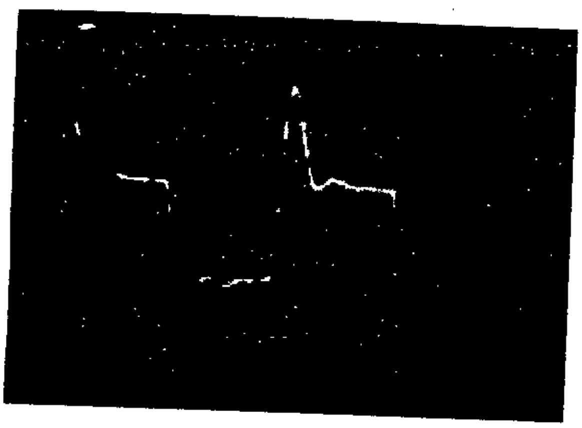
PLATE NO. 20

5.8. STUDY OF LIGHTNING SURGES FOR DISTURBANCE AT POINT 9-10.

1.C. Output voltage surges at the far end of section 8 (205 miles from the disturbance).



(a) 2v/cm and 5 m sec/cm.
output pulses for condition-1
(no load)



(b) 2V/cm and 5 m sec/cm output pulses for condition -2 (132v source replced by 0.8 p,f load).

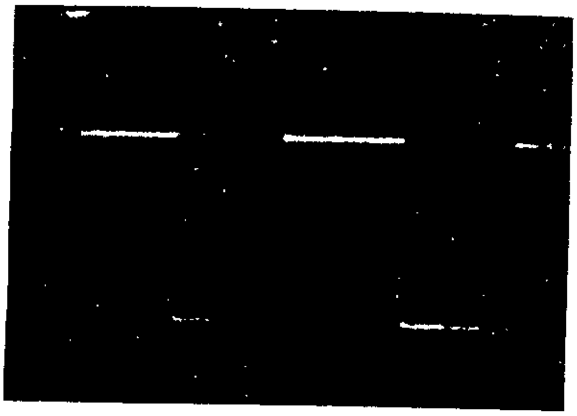
(c) 2V/cm and 5 m sec/cm output pulses for condition-3 (condition 2 and 0.85

PLATE NO. 21

5.9. SIMULATION OF LIGHTNING SURGES FOR DISTURBANCE AT POINT 1-2.

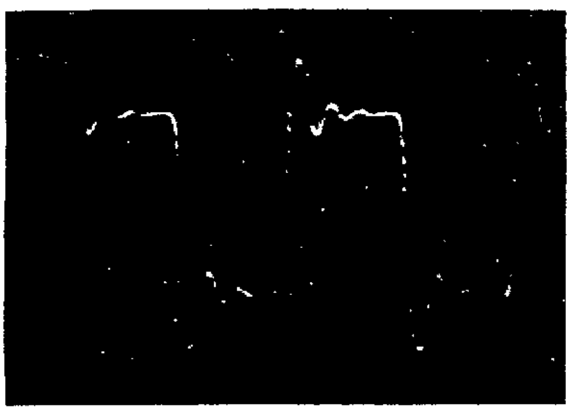
1.A Input pulses (7 v pp & 60 pps, input impedance 60 ohms) (fig.a,b)

2. (B) Output voltage surges at point 13-14 (180 miles from the disturbance) (fig.c,d) and (c) output voltage surges at point 4-5 (65 miles from disturbance) (figure e,f).

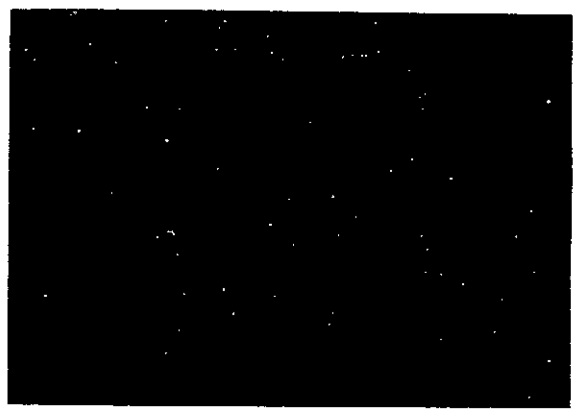


(a) 2v/cm and 5 m sec/cm input pulse before injection.

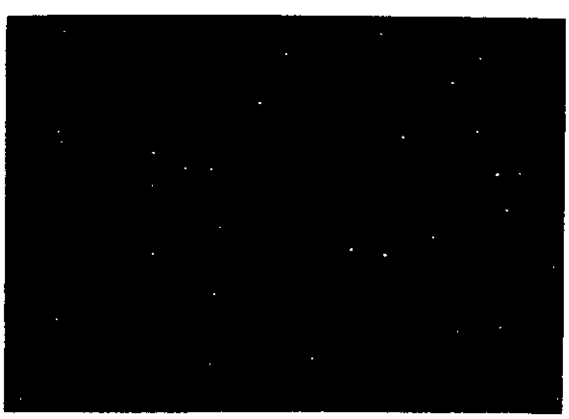
(b) 2v/cm and 5 m sec/cm input pulse after injection at point 1-2.



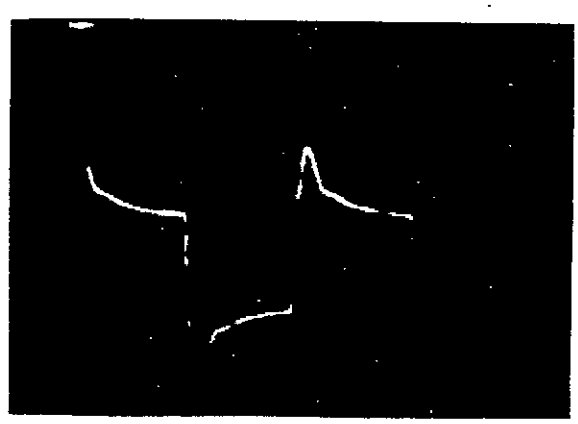
(c) 2v/cm and 5 m sec/cm. output pulse at 13-14 for condition-1 (no load).



(d) 2v/cm and 5 m sec/cm output pulse at 13-14 for condition-2.



(e) 2v/cm and 5 m sec/cm output pulse at point 4-5 for



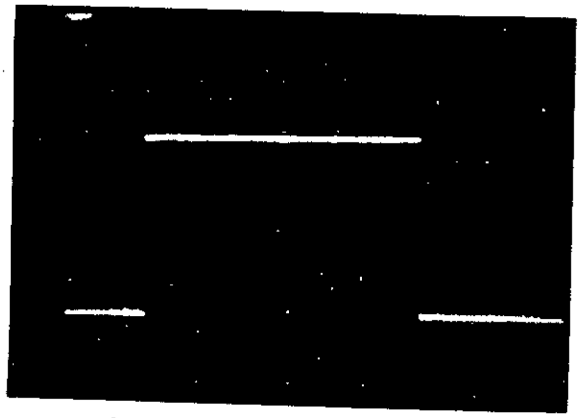
(f) 2v/cm and 5 m sec/cm output pulse at point 4-5 for condition 2

PLATE NO.22

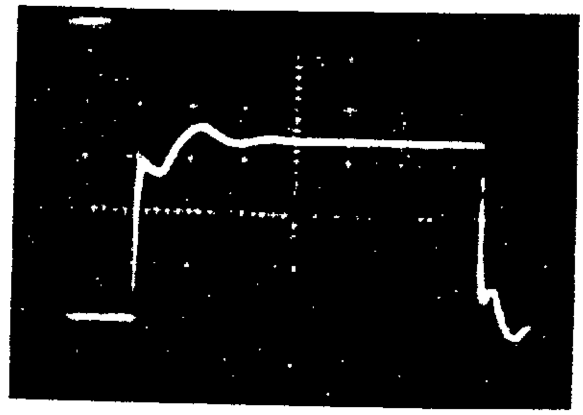
5.10 STUDY OF LIGHTNING SURGES FOR DISTURBANCE AT POINT 12-13.

1.A. Input pulses (7v pp, 20 pps input impedance 60 ohms,) (fig.a,b).

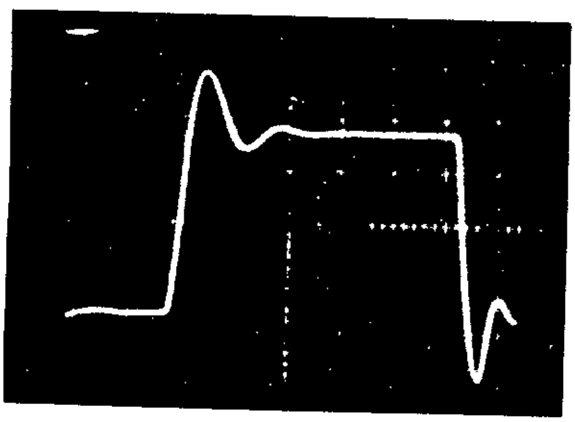
2 B. Voltage surges at point 4-5 (220 miles) from the disturbance) (figc,d,e) .



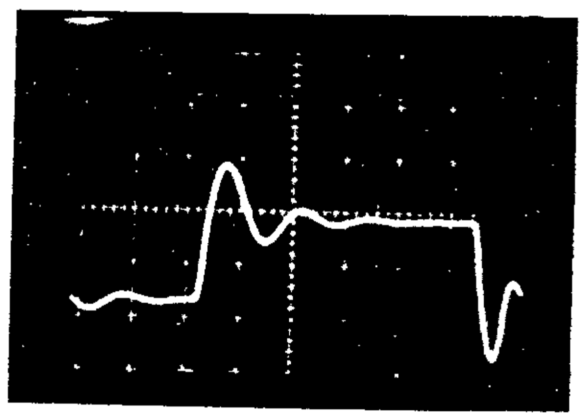
(a) 2 V/cm and 5 m sec/cm. input pulse before injection.



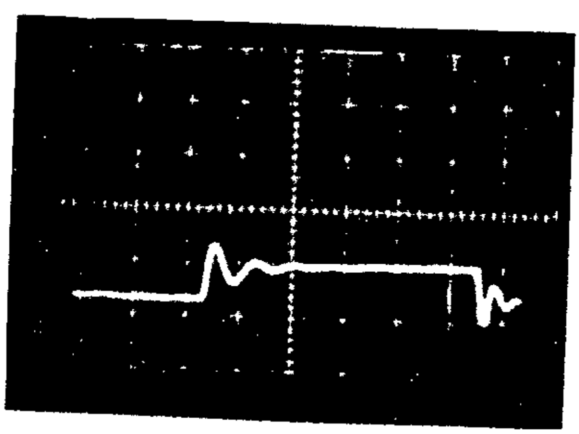
(b) 2 v/cm and 5 m sec/cm. input pulse after injection at point 12-13.



(c) 2v/cm and 5 m sec/cm. surges for condition-1



(d) 2v/cm and 5 m sec/cm surges for condition-2.



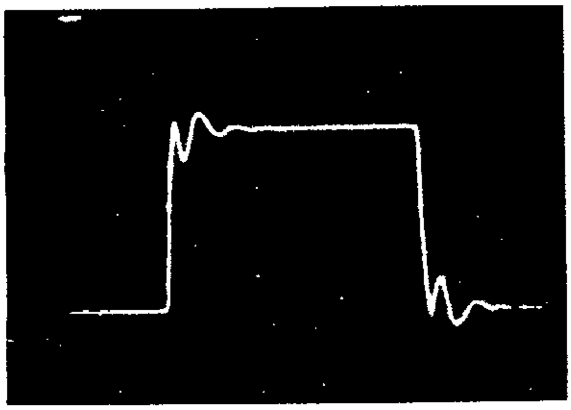
(e) 2 v/cm and 5 m sec/cm. output surges for condition-3..

PLATE NO. 23.

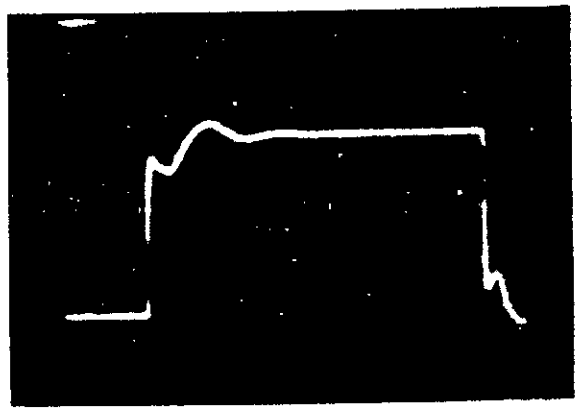
5.11 STUDY OF LIGHTNING SURGES FOR DISTURBANCES AT POINTS 3-4 & 12-13.

2.C. Voltage surges at point 8 (far end) (120 miles from the disturbance at point 3.4(fig.a,b,c) .

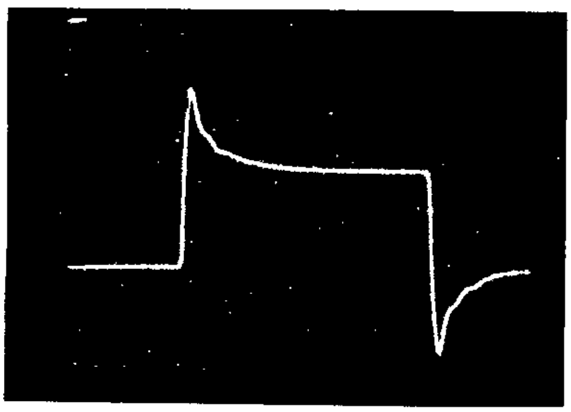
2.D. Voltage surges at point 13-14 (6 miles from the disturbance at point 12-13) (fig.d,e,f).



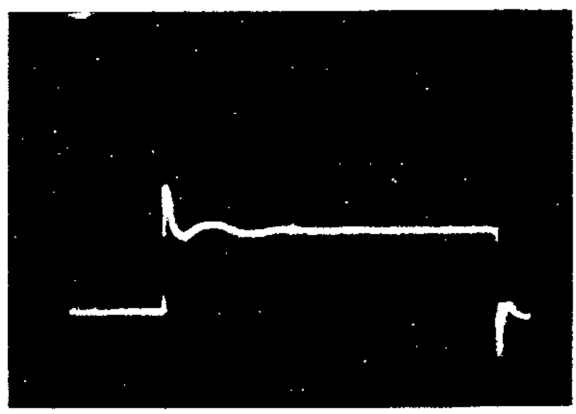
(a) 2v/cm and 5 m sec/cm. voltage surges for condition-1



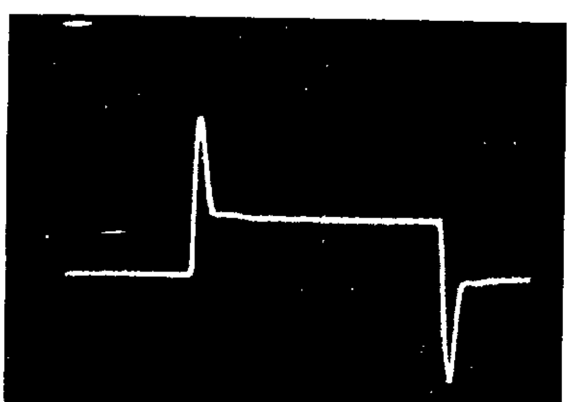
(d) 2v/cm and 5 m sec/cm. voltage surges for condition 1 .



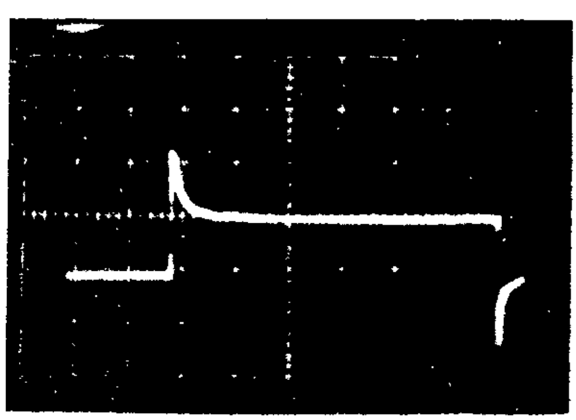
(b) 2v/cm and 5 m sec/cm. voltage surges for condition-2.



(e) 2v/cm and 5 m sec/cm voltage surges for condtion-2.



(c) 2v/cm and 5 m sec/cm voltage surges for condition-3.

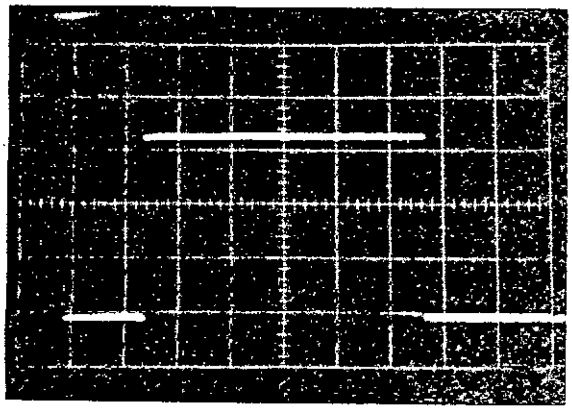


(f) 2v/cm and5msec/cm voltage surges for condtion-3.

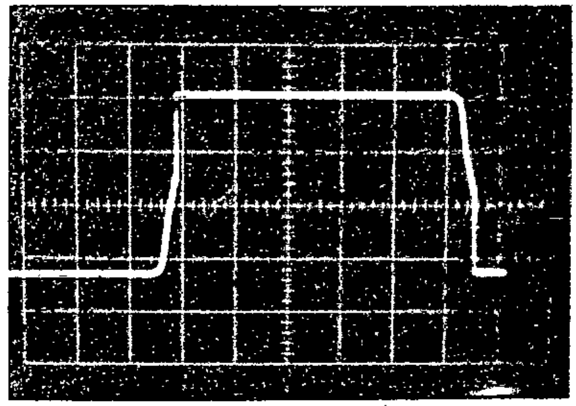
5.11. STUDY OF LIGHTNING SURGES FOR DISTURBANCE AT POINT 3-4.

1.A. Input pulses(7 v pp, 20 pps, input impedance 60 ohms.). (Fig. a,b).

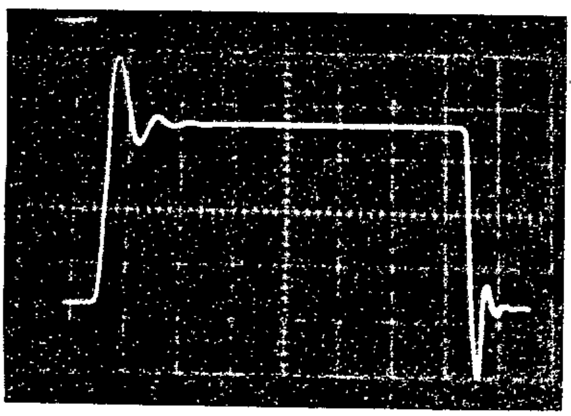
2. B. Voltage surges at point 11-12 (115 miles from the disturbance)(fig.c,d-e)



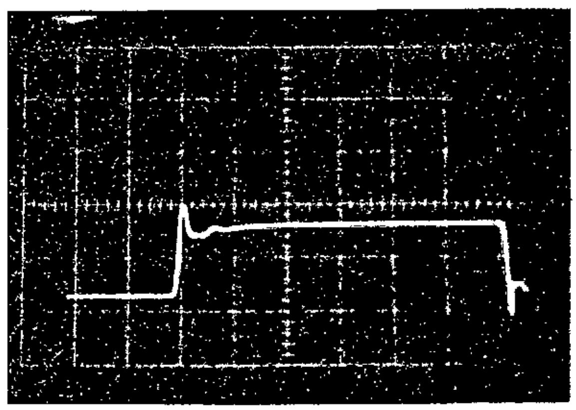
(a) 2v/cm and 5 m sec/cm.
input pulse before injection.



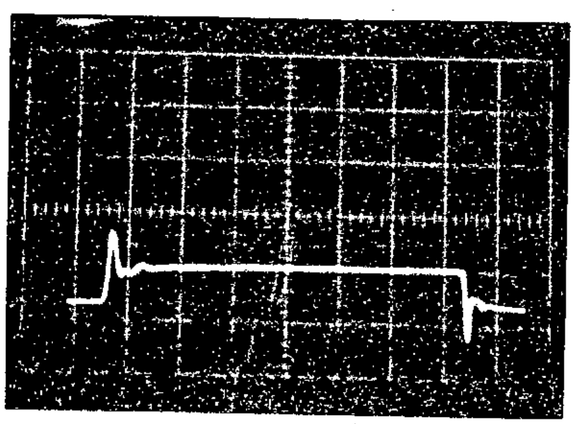
(b) 2v/cm and 5 m sec/cm.
input pulse after injection at point 3-4.



(c) 2 v/cm and 5 m sec/cm.
voltage surges for condition-1



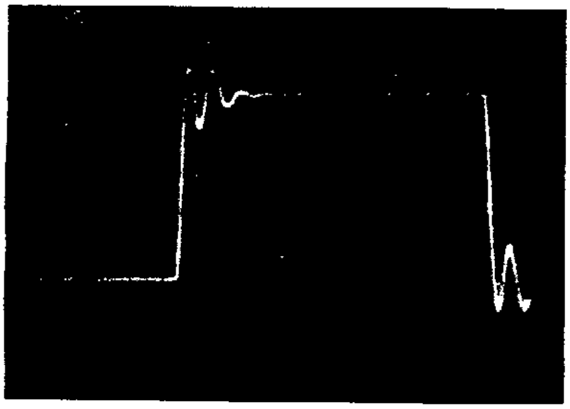
(d) 2v/cm and 5 m sec/cm.
Voltage surges for condition-2.



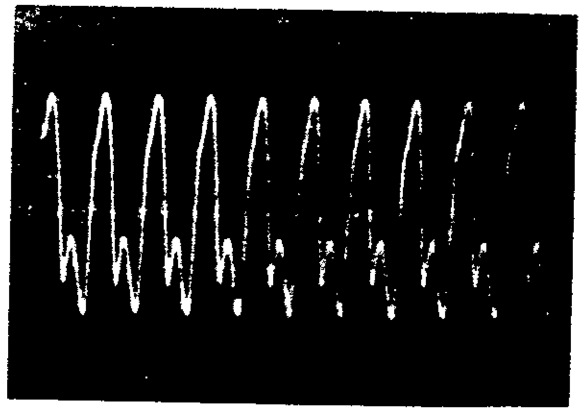
(e) 2v/cm and 5 m sec/cm.
Voltage surges for condition-3.

PLATE NO. 25

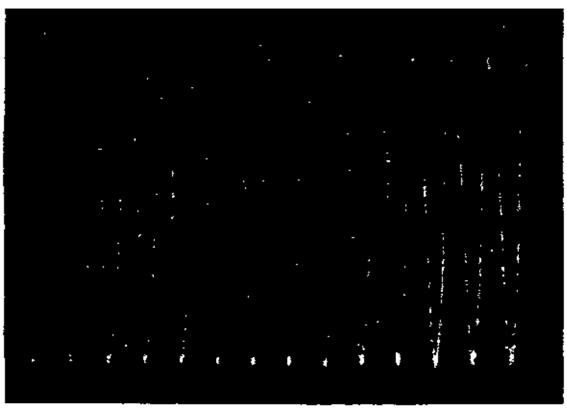
5-12 STUDY OF RESONANCE PHENOMENA AT POINT 13-14 FOR DISTURBANCE AT POINT 9-10 FOR NO LOAD CONDITION.



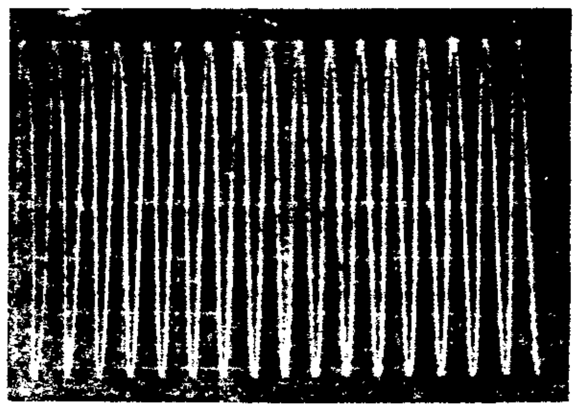
(a) 2v/cm and 5 m sec/cm.
Output surges at point 13-14 for no load condition. (Input 20 pps.)



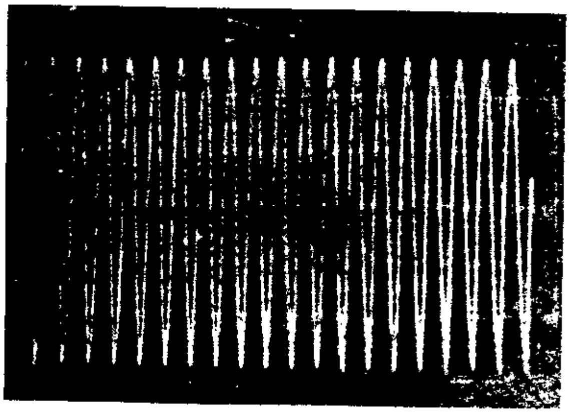
(b) 2v/cm and 5 m sec/cm.
Output surges (input200 pps)



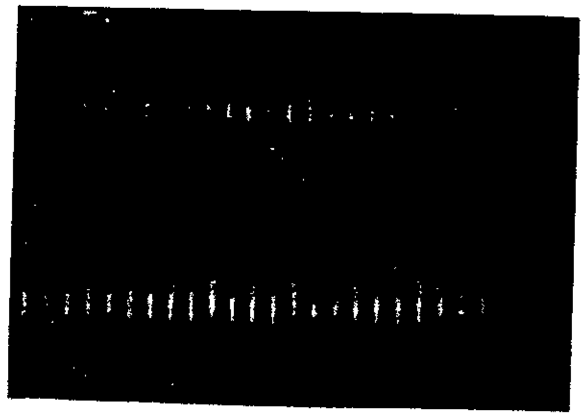
(c) 2 v/cm and 5 m sec/cm.
Output surge (input 280 pps)
(amplitude increased)



(b) 2v/cm and 5 m sec/cm
output surge (max.amplitude,
(for input 320 pps.)(near resonance



(e) 2v/cm and 5 m sec/cm.
Output surge (amplitude decreased)
(Input 400 pps).



(f) 2v/cm and 5 m sec/cm.
Output surge (further decreased).
(Input 500 pps).

Note: IN all the cases input amplitude 7 v pp & input impedance 60 ohms.

CHAPTER- 6

ANALYSIS OF RESULTS

6.1. ANALYSIS OF NO LOAD (STEADY STATE) VOLTAGE AND CURRENT:

The no load (open circuit) voltage and the charging current for the system are shown in Table-6(Page-63). The tabulated result shows that the voltages at different sections of the system increases with increasing distance from the source, although the exciting voltage is kept constant at 132V. For example at point 3-9 at a distance of about 170 miles the voltage rises to 205V and at the point 8(far end) at a distance of 325 miles this value is about 230V.

The maximum charging current of 0.42 Amp. is obtained at point 12-13 only 6 miles from the source. Thereby the current continues to decrease and becomes negligible at points near the end of the system. For example at point 9-10, 120 miles away, this value is 0.30 Amp. and at point 3-4, 200 miles from the source, is only 0.20 Amp. At point 5-6, at a distance of 255 miles, the charging current is almost negligible.

The rise of no load voltage and the decay of charging current with distances is shown graphically in plate no.29 (Page- 85).

The rise in voltage in an open circuited line with distance is due to "Ferranti Effect". Ferranti noted that on a long line which is lightly loaded or is at no load condition, the receiving - end voltage is greater than the sending-end voltage. Let us consider a single phase unloaded line. The current is due to the capacitance of the lines and is given by

$$I = jwclE_s,$$

Where $w = 314$ radians / sec.

and cl = line capacitance.

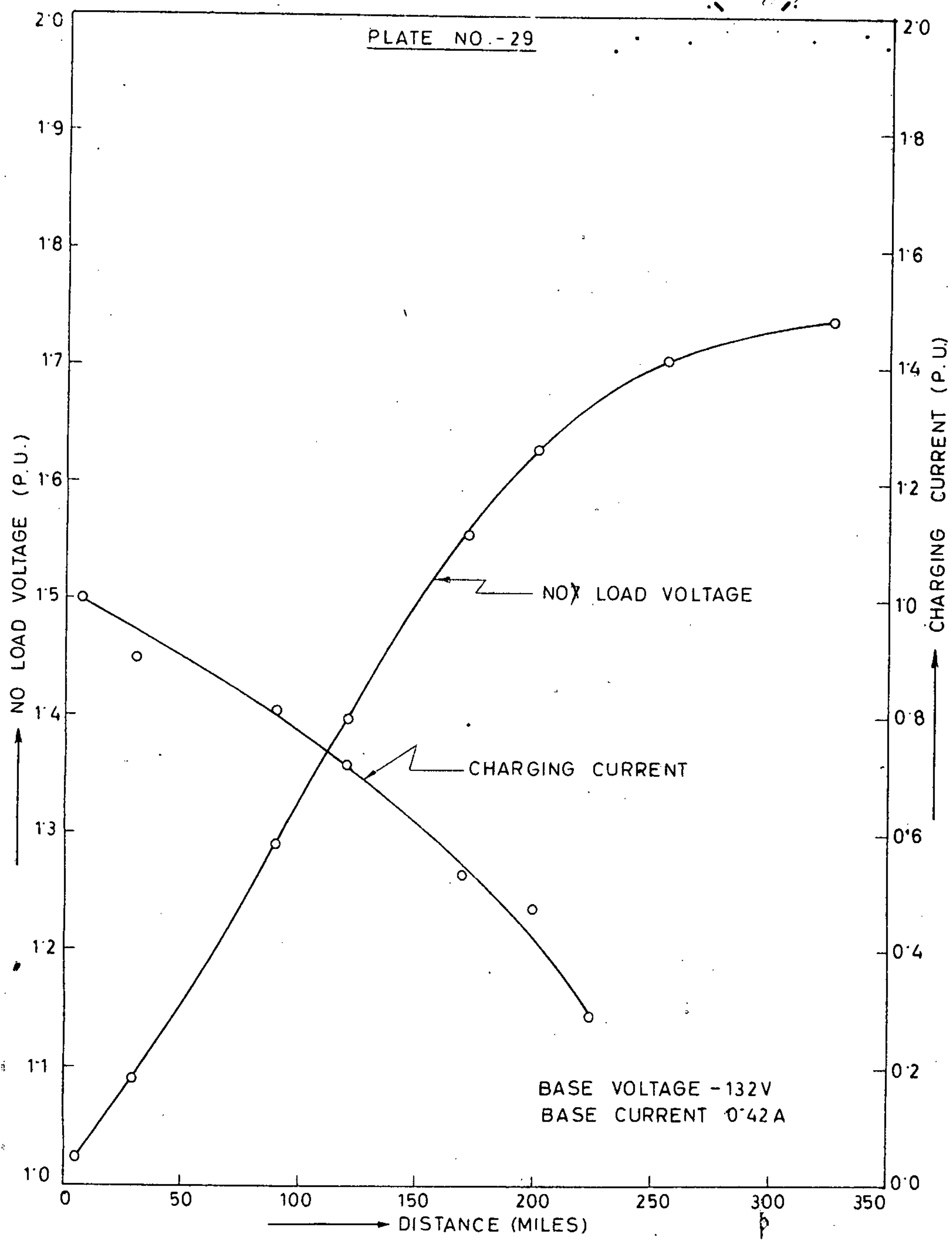


PLATE NO.-29
NO LOAD VOLTAGE
CHARGING CURRENT
BASE VOLTAGE - 132V
BASE CURRENT 0·42A
NO LOAD VOLTAGE (P.U.)
CHARGING CURRENT (P.U.)
DISTANCE (MILES)
0
50
100
150
200
250
300
350
1·0
1·1
1·2
1·3
1·4
1·5
1·6
1·7
1·8
1·9
2·0
0·0
0·2
0·4
0·6
0·8
1·0
1·2
1·4
1·6
1·8
2·0

The voltage drop is

$$jwL1I = -w^2Lcl^2 E_s,$$

and so that the receiving end voltage is

$$E_s + w^2LCl^2E_s = E_s(1+w^2Lcl^2).$$

For the 132KV Eastern grid of Bangladesh Power Network we have, on average,

L= 1.95 mh/mile and c=0.145 mF/mile.

The distance of Sylhet zone from the sending station Kaptai is 325 miles. If we assume that only the Kaptai hydro system sends power to the farthest end of line of Sylhet zone, than the noload voltage rise due to Ferranti effect is calculated as follows:

$$\Delta E = w^2Lcl^2E_s$$

$$= (314)^2 x\ 1.95\ x\ 10^{-3}\ x\ 1.45\ x\ 10^{-8} x(325)^2 x132KV.$$

$$= 38.5\ KV.$$

which means Shahgibazar- Sylhet Zone of the grid will have

132KV + 38.5 KV = 170.5 KV.

However the corresponding rise in no load voltage as obtained from the curve of page 85 is higher than this value. This is because the actual system is not evenly distributed and has a number of cables over river crossing increasing the system capacitances.

The rise in voltage for a lightly loaded or unloaded system is very dangerous for the system, because it creates severe stress on the system and apparatus insulation, levels. Thus it is expected that the grid net work should be always adequately and evenly loaded as far as possible to minimize the Ferranti effects-voltage rise.

6.2 ANALYSIS OF SWITCHING TRANSIENTS FOR RESISTIVE LOADS:

The system was initially in the unloaded condition. The resistive load (R= 80 ohms) was suddenly applied at an instant corresponding to point X on the oscillogram and again quickly disconnected atan instant corresponding to point Y on the oscillogram.

Let us consider the case when the load was applied at point 11-12, only 30 miles away from the 132V source. The corresponding voltage transients at points 12-13 (6 miles away), at point 10-11 (90 miles away) and at point 3-4 (200 miles away from the source) are shown in oscillograms-a,b and c of plate no.7(page 64).

A close observation of these oscillograms reveals that as we move away from the source, the noload voltage increases more and more because of the charging current (Ferranti effect). From the oscillogram-a it is observed that the noload voltage drops (point X) as soon as the load is applied at. And then continues to decrease slightly and within about 0.2 sec. reaches steady value. Again when the load was suddenly removed , the voltage instantaneously doubled (point Y) and continued to rise and within 0.3 sec. reached the steady no load value. Oscillograms-b and c showed the same characteristics. In these cases although the no load voltage values were much higher, the load voltages were equal to or even less than that of oscillogram-a.

From these, it can be concluded that beyond the load, the system voltage remains more or less constant, but the no load voltage continues to increase as the distance from the sources increases, because of Ferranti Effect. as discussed earlier.

If the oscillograms-d,e,f of plate no.7 and oscillograms-a,b c of plate no.8 were compared with the oscillograms-a,b,c of plate-

No.7, a point of interest is as follows: When the load was applied at a remote point from the source, during the switching on or off, the transition period decreases, that is the voltage quickly (by less than 0.1 sec) reached the steady value. Further the magnitude of the steady load voltage was greatly reduced, as the distance from the source as well as load increased.

For current transients consider the photographs-a, b, c, d and e of plate no.9. (Page 66). Oscillograms-a, b and d show that after switching-on the load the current instantaneously more than doubles and then the peak settles to a slightly less value within very short period (about 0.1 sec). During the switching-off condition, the current instantaneously falls to a value less than the noload charging current and then gradually rises to the noload charging value.

Let us now consider the cases 'b' and 'd' of plate no.9. These oscillograms show the current waves shapes beyond the load point and are very far away from the source. Here during the switching-on, the load the current unlike the cases-a, c, d, instead of rising instantaneously falls to a value much below the no-load charging condition. On the other hand during the switching off, the condition reaches the no load steady value by 0.2 to 0.5 sec. which indicates a corresponding the longer transition period.

Oscillograms-'d', 'e', and 'f' of plate no.8 reveal an interesting phenomena. Here the load is very far away (225 miles) from the source but current is observed only 6 miles away from the source at point 12-13. The current during the switching on condition jumps to very high peak value for one or two cycles only and then falls to value less than noload charging current and then gradually (by about 0.3 sec.) takes the steady no load value. During the switching-off con-

condition again there is a jump but this time, the transition period is less than the previous case (only 0.2 sec).The current as observed at a distance of 200 miles from the source at point 3-4, the current still jumps to a high value during switching-on condition, but here the transient period is extremely short (only about 0.1 second) and finally settles to a steady value higher than the noload condition.

A more interesting fact is revealed by oscillogram-f of plate no.8. The point of observation here is the load point, and during switching on condition the current instantaneously becomes zero and goes out of track and again during switching-off almost instantaneously reaches the steady value.

6.3. ANALYSIS OF SWITCHING TRANSIENTS FOR INDUCTIVE LOADS:

Plate no.10 (Page no.67) illustrates that the position of the load plays an important role in determining the steady state value of voltage at different points as well as the time required to reach this steady value.

For instance compare the figures-b and e, both give the voltage at point 9-10, but because of position of load, in figure-b the steady load value is appreciable and takes about 0.25 sec. to reach the steady value while in Fig.-e the steady value is negligible. In both the cases during switching-out the voltage rises sharply, In 1st case the load is 90 miles away whereas in the second case the load point coincides with the point of observation.

For current transients plate no.11 shows that for points within the load after switching-in, the current almost doubles instantaneously and reaches to a steady value by 0.2 to 0.3 seconds which is only slightly less than the steady value while during switching-out condition it very quickly rises to the steady no load value. For points near the load or beyond load, the no load charging current itself is of small value and during switching, instead of increasing sharply falls to a value which is almost negligible and during switching out very quickly (by about 0.1-0.2 sec) reaches the no load steady value.

6.4. ANALYSIS OF SWITCHING TRANSIENTS FOR CAPACITIVE LOADS:

Plate no.13 (Page no.70) shows an interesting result. Unlike resistive and inductive loads here during switch-in, the voltage instantaneously rises to a high value and gradually settles to a more higher value and during switch-out condition it gradually returns to the steady no load value but without any sudden jump.

The current transients unlike resistive and inductive loads rises at all points whether the point in question is within or beyond the load point. Here also the currents during switching-in quickly rises to a high value and instead of decreasing like resistive or inductive loads gradually increases slightly and settles to a steady value. But during switching-out it shows both types of behaviour, instantaneously reaching to lower value, then arriving to the no-load charging value either by decreasing or increasing slightly.

6.5. ANALYSIS OF SWITCHING TRANSIENTS FOR R-L LOADS:

The voltage transients for R-L loads as shown in plate no. 14,(Page No.71), closely resembles that for individual resistive and inductive loads. One important feature here is that when the load is applied to a far point (reference Fig. d and f of plate No.14) from the source, the voltages during switch-in and switch-out abruptly changes and comes to a steady value passing through a very short (less than 0.1 sec) transient period. But for a load near the source (ref.fig.a,b) the voltage during switch-in condition instantaneously lowers as usual and then settles to a further lower value after 0.2 - 0.3 sec. During switching-out the voltage sharply rises and then gradually reaches to a higher steady value. (reference Fig.a,b).

An interesting feature of this R-L voltage transients is that depending upon the position of the load and the point of record, there may not be any appreciable difference between no-load voltage and load voltage i.e. the system remains as if it has not been disturbed -(reference Fig. C of plate no. 14).

For two R-L loads i.e. when one R-L load is switched-in or switched -out keeping a second R-L load connected to the system at some other points (Fig.a,b,c of plate no.15), then the change in the voltage conditions of the system is very small.

The current transients as shown in fig.d,e of plate no.15 shows a transient of the same nature as those for resistive and inductive loads. For the case-d , in which the current is observed at point near the source and within loads points, there is a pronounced and very sharp rise (Point X) for switching -in condition . It then gradually decreases settling to a high steady value. Again during switching-out condition (point Y of Fig.-d), the current instantaneously falls to a value lower than no load value and thereby continues to rise to reach the steady no load value.

In Fig. e (point x) of plate no.15 it is seen that during the switching-in condition, where the current is observed at a point beyond the load point, the current instead of rising, sharply falls and then continues to decrease for about 0.2 sec. till it reaches a very low steady value, Here during switching-out condition it quickly rises but takes a much longer period (0.3 to 0.4 sec) to reach the steady value.

6.6. ANALYSIS OF SWITCHING TRANSIENTS FOR SHORT CIRCUIT CONDITION:

Consider figures-a, c and d of plate 16(page no.73). In all these cases the voltage transients are within the source and the short circuited point. Figure-a, c shows that although the no-load voltage for both of them are almost equal, during and after switching-in condition, the load voltage differs considerably. In this case of Fig.-a, the short circuited point is only 24 miles away and in the case of Figure -C the short circuited point is 124 miles away , hence in the latter case the load voltage is only slightly less than the no load voltage. In figure -a during switching-in the voltage instantaneously falls to almost half and then within 0.2 sec. reaches to the steady value. At point Y, during switching-out, it suddenly rises and continues to rise upward till attains the normal noload value.

Figures -b and e show the voltage oscillograms at points beyond the load point. Here during switching- in condition (Point X), the voltage quickly falls to zero without passing through any transition period. But during switching-out condition after sudden clearance of the fault (point Y) voltage sharply rises to an appreciable value and then gradually reaches the normal value by about 0.2 second.

The current transients as shown in Fig.a,b,c,d,e,f of plate no.18 (Page no.75) reveals some interesting points. All the three oscillograms-a,c,e, show the current transients at point 12-13, only 6 miles from the source. But because of different distances of the short circuited points, they are different.

In oscillogram-a where the fault point is only 26 miles away the value jumps to 4 to 5 times (point x) during switching - in condition and within very short time(0.1 sec.) reaches to a steady value which is about 3 times the normal value. Oscillogram-b shows a similar phenomena but as the distance here is about 115 miles from the fault condition, the magnitude is greatly decreased (about 2 times) as compared with oscillogram-a. In oscillogram-e, in which case the fault point is about 220 miles away , during switching-in condition, the current decreases instead of increase.

The oscillograms-b,d,and f, show a behaviour opposite to those of a,b,c, because of the change in position of the recorded oscillograms. Oscillograms -b and d are taken for points beyond the fault, hence here during switch-in condition, the currents sharply takes zero value;

The oscillogram-f compared with the oscillogram-e, shows an opposite behaviour. Here instead of decrease, the current increases after short circuits, although this point of observation is beyond the short circuited point.

6.7. ANALYSIS OF LIGHTNING SURGES FOR DISTURBANCES AT DIFFERENT POINTS OF THE SYSTEM:

Oscillograms-a and b of plate no.19 (Page no.77) show the input pulses. In Figure 'b' it is observed that after injection to the system, the front side of the input pulse is dipped down. The voltage surges at point 11_12 at different loads are shown in Figures-c,d,and e. The dipping of the input pulse is due to the mismatch of the system impedance with those of the input pulse.

Several significant points of interest are brought out in oscillogram-C. There is a pronounced voltage dip after the 1st crest and then the voltage again reaches a 2nd peak value which is equal to the 1st peak. The 2nd trough is not so pronounced as 1st one, again there is a 3rd peak whose magnitude is slightly greater than the steady value. Thus the oscillogram-c shows two oscillations of appreciable magnitude while the 3rd one is negligible. Another important point is that the peak to peak voltage rises to 9V from 6V i.e. rises by about 50%. The surge magnitudes and the oscillation frequency are shown in Table-7(Page no. - 97).

Oscillogram-d reveals that during load condition the surge greatly reduces in magnitude from 6V to 4.5V peak to peak. Here only one crest and one trough appears on the surge. For two loads connected with the system, the amplitude of the pulses further reduces although a sharp defined one crest and one trough still remains.

Plate No.20 (Page no.78) shows the surges at the far end of section 8 at a distance of 205 miles from the disturbance at point 9-10. Here (Oscillogram-a) during no load the surge rises to 11V peak to peak (about 80% increased) and has only one trough and is less pronounced then the crest. Oscillogram-b indicates that although 1st crest is more pronounced than oscillogram-a, but subsequently the surge greatly reduces, and becomes only 3 to 4 volt.

For two loads connected to the system the 1st crest is well defined and there is a minor 2nd crest, but the over all amplitude of the surge further reduces.(becomes less than 3V, although the input pulse is about 7V.).

Plate no.21 indicates for disturbance accuring at point 1-2, the surges at a point 13-14 (180 miles away)and at point 4-5 (65 miles away from the disturbance). These oscillograms reveal same features as those of oscillograms of plate no.20 with the exception that the input surge impedance at point 1-2 matches with the system impedance, so that the input pulse remain un-affected after injection at point 1-2.

The oscillograms of plate no.22, 23 and 24 illustrate the input pulses and the corresponding surge voltages and their nature of oscillations for disturbances being injected at point 12-13 and point 3-4. The important difference of these surge oscillograms with those of plate no.19, 20 and 21 is that because of the decrease in input pulse repitation rate from 60 pps to 20 pps, only one cycle of the pulse appears on the screen. The over all nature of surge propagation is same in both the cases. But these oscillograms, are more distinct and hence are more informative in nature.

The variation of surge magnitude with distances for no load as well as loaded condition of the system are calculated and is shown in tabular form (Table-7). The frequency of oscillations of these surges as they propagates along the system are shown in

6.8. ANALYSIS OF SURGE PROPAGATION: VOLTAGE PEAKS AND FREQUENCIES OF OSCILLATIONS :

The magnitude of the surge peak as it propagates along the transmission lines for injection of pulses at different points are measured from the oscillograms and shown in Table-7. The input pulse of 6.8V peak was 1st applied at point 12-13 and the surge voltage peaks were recorded at varying distances from the point of disturbances. The surges were observed 1st for the noload condition of the system and then repeated when the system was loaded.

Next the input pulses was applied at points (3-4) and (9-10) located some where near the middle of the transmission systems. The output surge voltage peak was noted as the disturbance was progressing in both the directions.

The tabulated results, were plotted as the 'surge voltage Vs. distance' curves . The curves of plate no. 27(Page No.98) represent the system at noload and those of plate no.28 (Page no.99) when the system is loaded.

All the curves of plate no.27 reveal that the surge peak increases with the increase of distance when the system is unloaded (i.e. no load is connected to the system.) Curves 2 and 3 of plate no.27 show an interesting behaviour of the system. When the surge voltage reaches a junction point, the surge propagates in two different paths with great change in their peak values. This results because when the surge reaches a junction point the circuit parameter as well as the surge impedances are also changed. This creates a difference in the magnitude of the voltages to be transmitted and reflected back.

TABLE-7

SURGE VOLTAGE PEAK VALUES WITH DISTANCES

No. of obser-vation	Pulse injected at points	Input peak value (V)	Surge voltage measured at points	Distance from injected points (Miles)	Peak for no load (V)	Per unit value base 6.8V or 5.8V	Peak for 0.8 pf. load at (13-14) V	Per Unit value base 6.8V or 5.8V.	Distance from the load (miles
1	12-13	6.8	13-14	6	7.2	1.06	6.0	0.383	0
2	12-13	6.8	11.12	24	7.6	1.12	5.0	0.735	30
3	12-13	6.8	9-10	115	8.8	1.295	4.8	0.706	120
4	12-13	6.8	1-2	176	9.2	1.352	5.4	0.795	180
5	12-13	6.8	4-5	220	9.4	1.38	5.4	0.795	225
6	12-13	6.8	(8 farend)	320	9.6	1.41	5.6	0.824	325
1	3-4	6.8	3-9	28	7.3	1.072	2.8	0.412	170
2	3-4	6.8	9-10	80	8.1	1.186	3.2	0.461	120
3	3-4	6.8	11-12	170	9.2	1.355	3.6	0.53	30
4	3-4	6.8	13-14	200	9.4	1.382	2.8	0.412	0
5	3-4	6.8	4-5	28	7.6	1.12	6.2	0.913	225
6	3-4	6.8	(8 farend)	132	7.6	1.12	6.8	1.00	325
7	3-4	6.8	1-2	38	7.4	1.09	5.8	0.853	180
1	9-10	5.8	3-9	50	8.0	1.38	6.4	1.105	170
2	9-10	5.8	4-5	180	8.4	1.45	6.8	1.172	225
3	9-10	5.8	(8 farend)	210	8.8	1.515	7.4	1.275	325
4	9-10	5.8	11-12	90	8.0	1.38	4.4	0.758	30
5	9-10	5.8	13-14	120	7.8	1.345	3.4	0.517	0
6	9-10	5.8	(1 farend)	70	8.2	1.415	6.4	1.05	190

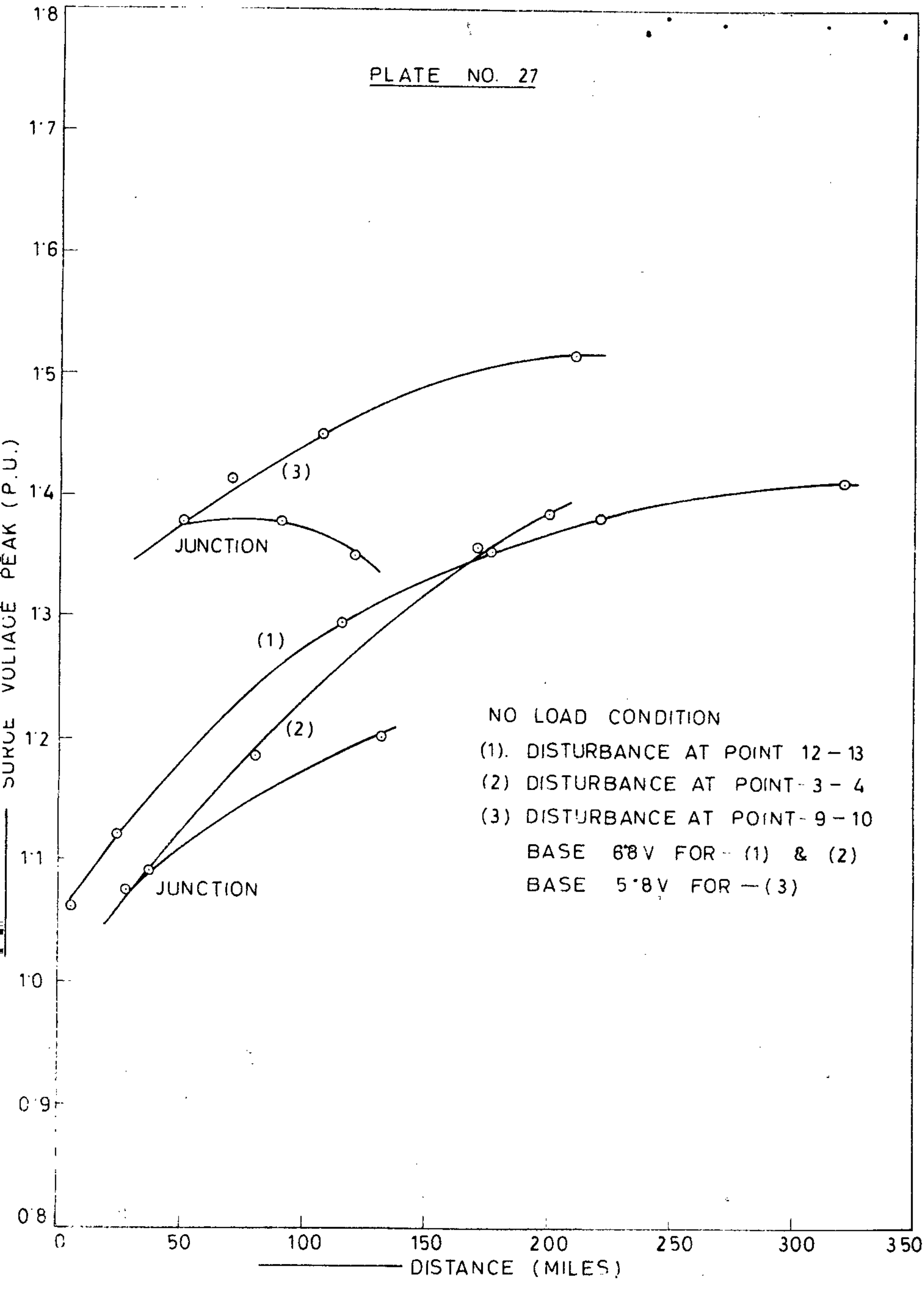


PLATE NO. 27
SURGE VOLTAGE PEAK (P.U.)
1·8
1·7
1·6
1·5
1·4
1·3
1·2
1·1
1·0
0·9
0·8
0
50
100
150
200
250
300
350
DISTANCE (MILES)
(3)
(1)
(2)
JUNCTION
JUNCTION
NO LOAD CONDITION
(1). DISTURBANCE AT POINT 12 – 13
(2) DISTURBANCE AT POINT - 3 – 4
(3) DISTURBANCE AT POINT - 9 – 10
BASE 6·8 V FOR - (1) & (2)
BASE 5·8 V FOR – (3)

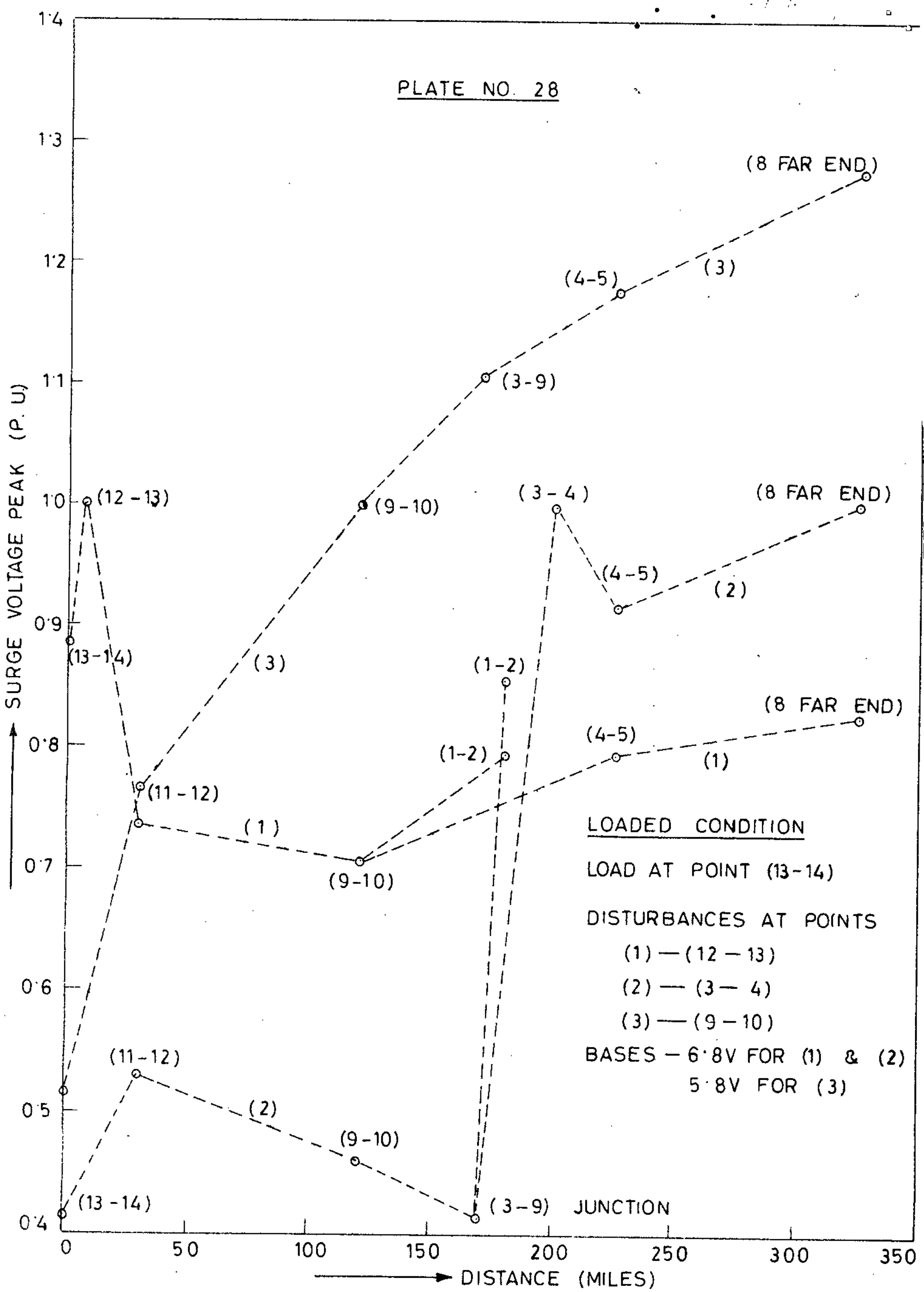


PLATE NO. 28
SURGE VOLTAGE PEAK (P. U)
DISTANCE (MILES)
1·4
1·3
1·2
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0
50
100
150
200
250
300
350
(8 FAR END)
(4-5)
(3)
(3-9)
(12 - 13)
(9-10)
(3 - 4)
(8 FAR END)
(4-5)
(2)
(13-14)
(3)
(1-2)
(8 FAR END)
(4-5)
(1-2)
(1)
(11-12)
(1)
(9-10)
(11-12)
(2)
(9-10)
(13-14)
(3-9) JUNCTION
LOADED CONDITION
LOAD AT POINT (13-14)
DISTURBANCES AT POINTS
(1) — (12 — 13)
(2) — (3 — 4)
(3) — (9 — 10)
BASES — 6·8V FOR (1) & (2)
5·8V FOR (3)

The curves of plate no.28 shows the surge propagation characteristics when the system is loaded. These curves are complex and the nature of propagation of the surge as the distance increases are still more complex. Because the nature and position of the load greatly influences the magnitude of the surges and the amount of transmission as well. In the loaded system there is a marked difference in the nature of the surge propagation at a junction point.

A comparison of the noload curves of plate no.27 with the load curves of plate no.28 clearly manifests the more complicated nature of the propagating surges for loaded system to those of the unloaded systems. The behaviour and the rate of decrease of the surge peaks for both the loaded and unload system can be easily explained by travelling waves theory however that is beyond the scope of the present work.

SURGE OSCILLATION FREQUENCIES MEASUREMENT:

For easy visualization of the nature of oscillations of the surges, the frequencies of the surges were measured from the oscillograms and is recorded in Table-8. The table shows that for disturbances at point-(12-13) at one end of the system, the frequencies of oscillations are 130 to 145 cps, for noload condition. When a load is applied at point 13-14, only 6 miles away, the frequencies of oscillation remain almost unaffected. Next when the disturbance was applied at point 3-4 the oscillation frequencies increases and lies in the range 290 to 325 cps and for loaded condition the surge voltage has no appreciable oscillations. Yet another disturbance at point 9-10, somewhere at middle position of the system was applied with input pulse repitation rate of 60 pps. instead

TABLE-8

SURGE OSCILLATION FREQUENCIES

No. of observation	Input pulses injected at points	Pulse repetition rate (pps)	Surge measured at points	Distance from the in- (K[illegible])	Freq. at no load (cps)	Freq. at 0.8 pf. load at point (13-14) (cps)	Distance of load from the point of measurement (miles)
1	12-13	20	13-14	6	1[illegible]	143	0
2	12-13	20	11-12	2[illegible]	200	133	30
3	12-13	20	9-10	115	143	[illegible]	120
4	12-13	20	1-2	176	143	143	180
5	12-13	20	4-5	220	143	200	225
6	12-13	20	(8 farend)	320	133	143	32[illegible]
1	3-4	20	3-9	28	286	-	170
2	3-4	20	11-12	170	323	-	30
3	3-4	20	13-14	200	308	-	0
4	3-4	20	4-5	23	286	-	225
5	3-4	20	(8 farend)	132	323	-	325
6	3-4	20	1-2	38	-	-	180
1	9-10	60	3-9	50	-	-	170
2	9-10	60	4-5	108	286	200	225
3	9-10	60	(8 fa[illegible])	210	286	200	325
4	9-10	60	11-12	90	323	-	130
5	9-10	60	13-14	120	323	-	0

TABLE-9

RESONANCE PHENOMENA.

Pulse with varying repitation rate injected at point 9-10 and observed at point (13-14) for no load condition of the system. 6·8V pulse (input) amplitude.

No.of observation	Pulse repitation rate pps.	Surge amplitude	Remarks
1	20	6.8	Amplitude increases.
2	200	8.2	
3	280	11.4	
4	320	12.3	resonance
5	400	11.5	amplitude decreases
6	500	10.0	

of 20 unlike the previous cases. These oscillation frequencies are almost similar to the case for disturbance at point 3-4 having input pulse repitation rate of 20.

6.9. ANALYSIS OF RESONANCE PHENOMENA.

Oscillogram -a of plate no.25 (Page No.83) shows the oscillations occuring at point 13-14 at noload condition when the disturbance occurs at point 9-10 having a repitation rate of 20 pps and 7 volts peak value. The point is about 120 miles away from the disturbance point. The repitation rate was then increased in steps and the corresponding output pulses at point 13-14 recorded, and is shown in Table-9.

It is observed that the highest amplitude occurs at about 320 pps (reference Fig.d of plate no.25). and the amplitude decreases for both higher and lower repitation rates (figure b,c,e and f of plate no. 25) . The pulse repitation rate of 320 is almost equal to the frequency of oscillation for this condition as recorded in Table-8.(Page no.101).

In this case the system frequency is 50 HZ and thus 320 HZ is near the 7th harmonics of the fundamental frequency. From this result, thus it may be concluded that at point 13-14, the system natural frequency consisting of system capacitances and inductances is nearly equal to the 7th harmonics.

Finally we can conclude that as a transmission system possesses resistances, inductances and capacitances; a near resonance or partial resonance condition may occur giving rise to a very high voltage surge (3 to 5 times or even higher) when the system natural frequency equals to the 5th or 7th harmonics of the fundamental during a disturbance.

CHAPTER - 7

CONCLUSIONS

7.1. CONCLUSION:

From the study of the switching voltage surges for resistive and inductive loads and short circuit conditions, it was observed that the most severe cases occur for the fault conditions. The operating voltage drops considerably for switching -on of heavy loads from the light-load and noload conditions. On the other hand sudden switching off operations of heavy loads, a sharp voltage rise occurs. The switching current transients for fault conditions only are important.

The magnitude as well as the durations/oscillations in a of system for lightning discharge is more pronounced for a light-loaded system. For an adequately loaded system the magnitude of the surge and its associated oscillations decay very rapidly as it progress on both sides from the disturbance point.

Only the 5th and 7th harmonic oscillations of the fundamental frequency are important for resonance over voltages. These may arise from the distorted voltage wave shapes because of transformer saturation, or the non synosoidal wave forms of the alternators.

7.2. FUTURE RESEARCH AREA:

The transient studies of a power system is of great importance , for with switching processes and lightning discharges peculiar phenomena appears which greatly disturbs the the regular operation of the system. Thus it was felt that a study of the transient phenomenon of the existing power net work of Bangladesh would be of value. With this view a Transient Analyzer was designed and built and for the first time a through and useful studies of the transients of the existing system were carried out and some valuable information regarding switching and lightning surges obtained. However it is suggested that further research work in this field is to be undertaken for improved and reliable operation of the system. Some of them are:

(1) Study of the transient recovery voltage characteristics of Circuit Breakers. The action of a circuit breaker may be simulated by arranging various recurring synchronous switches.

(2) Study of ferroresonance phenomena due to transformer saturation and its effect on the system performance. A single phase 1:1 turn ratio transformers having special saturation characteristics may be utilized to simulate those of large power transformers.

(3) Study of lightning arrester switching surge performance. This may be done by providing miniature tyrite arresters for simulating arrester of almost any voltage rating.

(4) Digital Computer Programme simulation for transient studies and

(5) Co-ordinated use of Transient Analyzer and Digital Computer for simulating complex switching and lightning surges.

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APPENDIX-A

CONVERSION OF LINE CONSTANTS TO PER UNIT (P.U.) AND VICE VERSA.

Voltage, current, 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.) Impedance of a circuit element

$$= \frac{\text{Actual impedance in ohms}}{\text{Base impedance in ohms.}}$$

Since three phase circuits are solved as a single line with a neutral return, the bases for quantities in the impedance 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 & C AT NEW BASE OF 132V AND 100VA FROM P.U. VALUES AT 132 KV AND 100 MVA BASE.

$$\text{Base Impedance } Z_b = (\text{base KV})^2/\text{Base MVa ohms.}$$

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

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

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

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

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

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

(1) Tongi-Ullon Section

$$Z_\pi = (0.0112 + j0.0437) \times 174 = 1.9488 + j7.6038\ \Omega$$

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

$$b/2 = \frac{j0.0049}{174} = j\ 2.816 \times 10^{-5} \text{ mho}$$

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

2. Ullon- Siddirganj Section:

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

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

$$b/2 = j0.00366\ /174 = j2.105 \times 10^{-5}\mho,\ C/2 = \frac{2.105 \times 10^{-5} \times 10^6}{314} = 0.067 \text{ mF.}$$

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

APPENDIX-B

MEASUREMENT OF INDUCTANCES (28) (29)

1. AMMETER- VOLTMETER METHOD:

Inductances of about 20 to 500 millihenries can be measured by this method. It is suitable for iron cored coils, since the full normal current to be carried by the coil can be passed through it during measurement. An improvement upon this method is done by connecting a non-inductive resistance in series with it.

A suitable current of normal 50 HZ frequency, is passed through the coil and this is measured by an a.c Ammeter. While the voltage drop across the coil and the non-inductive resistance is measured by a high resistance voltmeter. (for Fig. refer page 113)

The d.c. resistance r of the coil which will be the same as the a.c. resistance, to a close approximation, as the frequency is low, is also measured. Then the inductance L of the coil is given by

$$L = X_L / w = \sqrt{(Z_{coil}^2 - r^2)} / w \quad \text{henry} \approx \sqrt{Z_{coil}}/w = \frac{\sqrt{X_L}}{w}$$

Where $Z_{coil} = \frac{V_{coil}}{I}$ = impedance of the coil. and $\omega = 2\pi f$, f = frequency, 50 Hz.

For a iron-core coil of low resistance to reactance ratio the above relations hold good because $X_L \gg r$.

2. MODIFIED HAY BRIDGE FOR MEASUREMENT OF INDUCTANCE (29)

The Hay bridge differs from the Maxwell's Bridge only in having a resistance in series with the standard capacitor, instead of in parallel with it. On the other hand in the Modified Hay Bridge the unknown inductance is shown as parallel components, instead of series ones. This arrangement results in a simple formula for the unknown inductance in terms of the bridge parameters.

PLATE NO - 26

Circuit diagram for measurement of inductance.

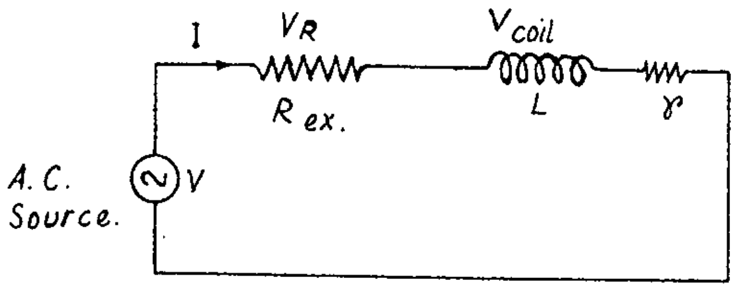
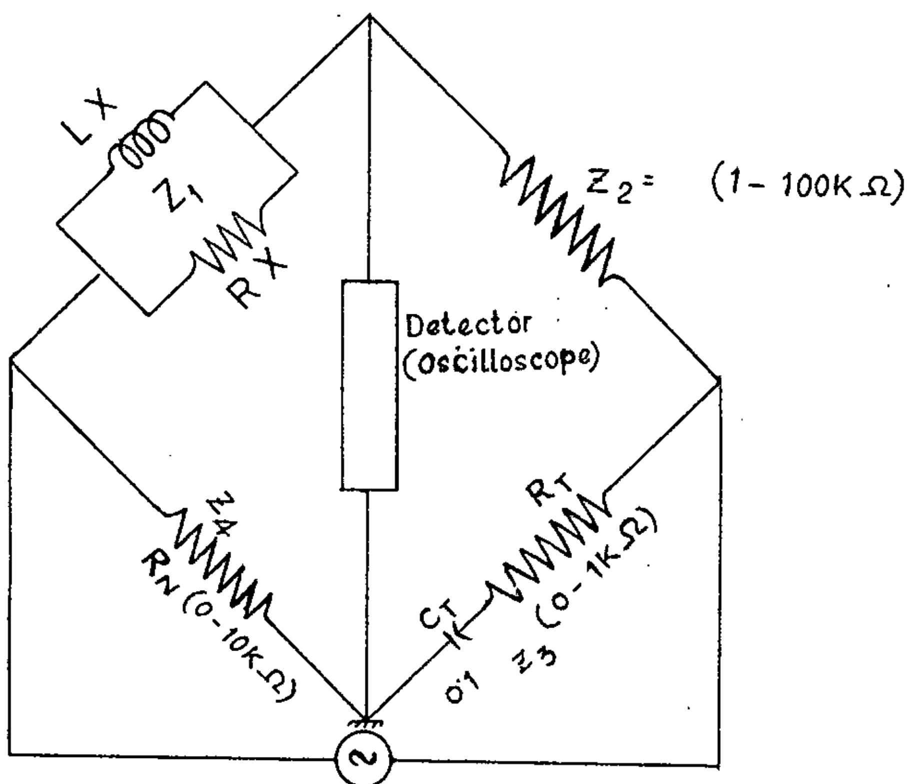


Fig. A. Ammeter Voltmeter Method



A. C. Source(L.F. Oscillator)

Fig. B. Modified Hay Bridge Method.

For circuit diagram of this bridge refer Fig.B of plate No. 26 of page no. 113. For no current flowing in the detector, i.e. at balance

$$Z_1 Z_3 = Z_2 Z_4 \qquad -(1)$$

The impedances for this case

$$Z_1 = \frac{R_x \times jwL_x}{jwL_x + R_x} \quad , \; Z_3 = R_T - j\frac{1}{w\,C_T}$$

$$Z_2 = R_A \text{ and } Z_4 = R_N \qquad -(2)$$

And substituting in equation (1)

$$\left(\frac{(jwL_x \times R_x)}{(jwL_x + R_x)}\right) \times \left(R_T - j\frac{1}{wC_T}\right) = R_N R_A. \qquad -(3)$$

$$\text{or } jwL_x R_x R_T + \frac{L_x R_x}{C_T} = jR_N R_A wL_x + R_x R_N R_A. \qquad -(4)$$

Equality of two complex number requires that the real parts be equal on both the sides of the equation which gives the unknown inductance and the resistance of the inductance coil as

$$L_x = R_A R_N C_T \text{ and } R_x = \frac{R_N R_A}{R_T} \qquad -(5)$$

This bridge was assembled in the laboratory with decade resistors and decade capacitors with the values as shown in the circuit diagram . The detector used was an oscilloscope while a L.F. Oscillator was the exciting A.C. Source. The bridge thus formed was tested for known value of inductance and was found to give fairly accurate value. Then the inductances of all the reactors constructed was measured, the result was found to be fairly accurate as obtained by the voltmeter Ammeter method.

THE END

T. 57.