INVESTIGATIONS ON SINGLE PHASE EARTH RETURN SYSTEMS FOR RURAL DISTRIBUTION

A thesis submitted in partial fulfilment
of the requirements for the degree of
MASTER OF ENGINEERING
in
POWER SYSTEM ENGINEERING

By
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1965

CERTIFICATE

Certified that the dissertation entitled ....INVESTIGATIONS ON SINGLE PHASE EARTH RETURN SYSTEMS FOR RURAL DISTRIBUTION which is being submitted by Sri V.G.POTEY in partial fulfilment for the award of the Degree of Master of Engineering in POWER SYSTEM ENGINEERING of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of ......10.......... months from .1st December.. to. 30th September .... for preparing dissertation for Master of Engineering Degree at the University.

Signature ....

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Dated..20th Oct '66..........

ACKNOWLEDGEMENTS

The author wishes to acknowledge his profound sense of gratitude to Dr.T.S.M. Rao (the then Associate Professor in Electrical Engineering, University of Roorkee, Roorkee and at present Professor and Head of the Electrical Engineering Department, Malviya Regional Engineering College, Jaipur) for his expert guidance and continuous encouragement, without which it would have been impossible for the author to bring the work to this stage.

The author wishes to thank Dr.O.P.Kulshreshtha, Reader in Electrical Engineering, University of Roorkee, Roorkee, for rendering invaluable help in planning and executing the experimental work.

The author thanks Pro. C.S.Ghosh, Head of the Electrical Engineering Department, University of Roorkee, Roorkee for his continued interest and various facilities offered in the department.

Sincere thanks are also due to the Central Board of Irrigation and Power for financing this investigation as a part of Basic and Fundamental Research Scheme at the University of Roorkee, Roorkee.

V. G. POTEY

CONTENTS

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SYNOPSIS

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In the rural areas of our country, loads are very small, and scattered not justifying 3-phase supply on economic grounds. The use of less costly single phase earth return system is advocated herein, for such areas where the immediate and future load demands are very small. The problems involved in the use of earth as return conductor are analysed in detail. . The model tests are conducted to study the interference with neighbouring communication lines, the gradient problem and to explore the means of reducing surface potentials near the earth electrode. Field tests help to check the results obtained by analytical and model methods. A simple protective scheme is devised to provide protection against high resistance earth faults on such lines. A simple static over voltage relay is developed to prevent build up of hazardous potentials near the earth electrodes. The need to make available single phase motors required in the rural areas at reasonable cost, and the use of existing 3 phase motors on single phase supply in conjuction with a capacitor or through phase converter is strongly advocated. The cost of the 3 phase transmission system and the single phase earth return system is worked out to show the saving in capital investment by use of the single phase earth return system.

CHAPTER 1

INTRODUCTION

INTRODUCTION

The extent of rural electrification in India may be seen from the fact that although 80 percent of the population is in villages, less than 8 percent of the villages are electrified. Finance constitutes the major difficulty in extending the benefits of electricity to the rural population. Economies in the initial investment costs with regard to rural distribution systems are necessary in view of the fact that the net return on such schemes is small and in m any instances they have to be subsidised by the State. In the rural areas of our country, loads are small and isolated, not justifying three phase supply on economic grounds. While ways and means have been adopted to overcome the excessive cost, the cost reduction in the existing supply has usually not been effective. Moreover, most of the loads in these areas need only single phase supply. Under these circumstances, it is thought prudent to investigate the apparently less constly single phase earth return system which does away with cross arms, one metallic conductor and its associated insulation.

Schematic diagram of the single phase earth return system suggested is illustrated in Figure 1. The entire electrification of such areas except the

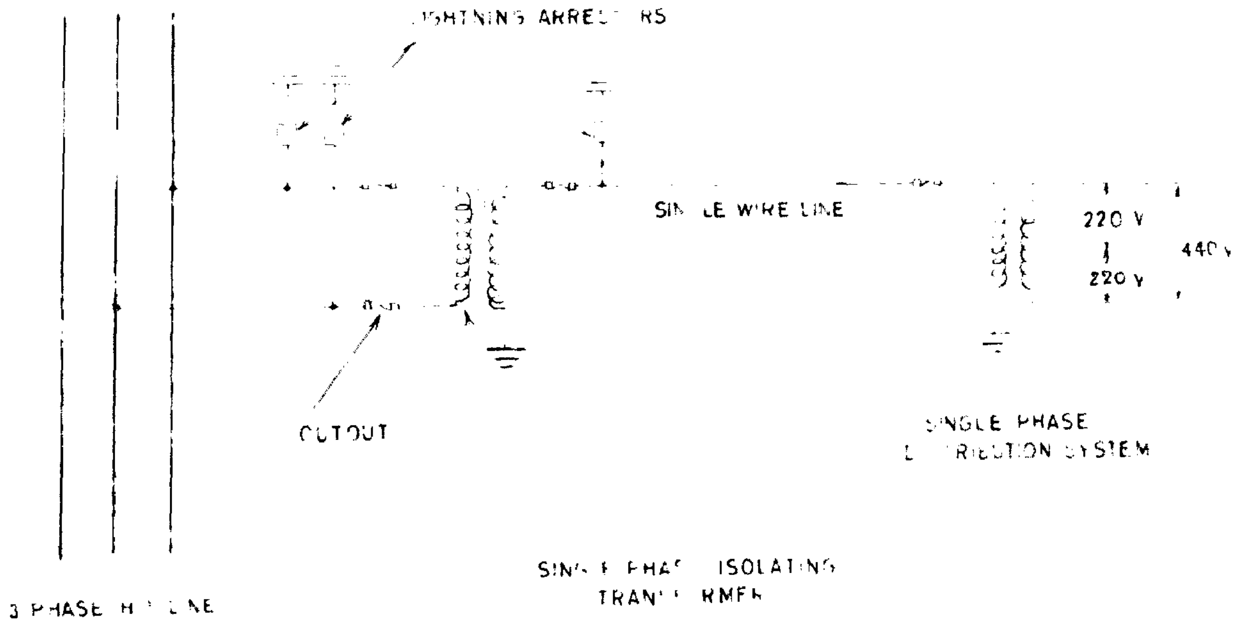

FIG.1.1 SCHEMATIC DIAGRAM OF THE SINGLE PHASE EARTH RETURN SYSTEM

final distribution stage, can be done by a single phase single conductor line using ground as return and taking power from high voltage substation of a standard 3-phase circuit. The single phase isolating transformer isolates the single phase earth return system from the 3-phase system. The final distribution is done by complete metallic circuit, consisting of three wire supply to the consumers, giving the advantage of two voltages, 220 and 440 volts for domestic and motor loads corresponding to the present three phase four wire system.

The idea of using ground return for power lines is not a new one. Trial installation of the single phase single wire earth return systems were placed in service in 1950 by New Zealand (1). In the province of Manitoba in Canada hundreds of miles of rural lines had been installed using ground as return path. In the U.S.S.R. (2) the use of ground as third conductor in three phase transmission is widely applied in 10 KV, 35 KV transmission net work. In India, Bihar and Maharashtra State Electricity Board have installed, as an experimental measure, 11 KV single phase single wire line. Although this system is used in many countries and is in experimental stage in some other countries, no information is available regarding the protective arrangements made and equipment used for the purpose. Moreover, the problems involved in the use of this system have not yet been analysed completely. In this dissertation, the problems involved in the use of single phase earth return systems with particular reference to the conditions existing in India, have been studied in detail.

The earth has been used as a conductor for electric currents since the very beginning of electrical engineering practice. But due to the following difficulties, the use of earth return for power lines has not been adopted as a general practice :

(1) Hazards due to the building up of voltage at the ground terminal due to high earth resistance of the terminal.

(2) Interference with communication circuits using ground return.

(3) Difficulties in relaying.

It is of primary importance to see that the potential rise over the ground surface is not excessive and that life of human being and animals is not endangered by such potential rises. The building up of the voltage at the ground terminal can be kept sufficiently low by obtaining suitable value of low earth resistance which is the root cause of the voltage gradients.

Interference with communication circuits using ground return has been one of the most effective arguments against using a ground return for power lines. However, when the matter is viewed more realistically, it would be found that the interference problem is relatively less significant.

The model tests have been conducted in the wooden electrolytic tank for determining the voltage gradient patterns due to different configuration of the grounding electrode and for studying the mutual inteference with neighbouring communication line. Field tests have been conducted on the experimental single phase single wire line to establish the theoritical investigations as well as to check the results obtained from model tests.

This system can be protected for overcurrent, and fusing or tripping would occur depending on the fuse/relay setting and the nature of the severity of fault. This system can be protected against high resistant earth fault, by superimposing d.c. on single phase a.c. with the circuitry such that d.c. would normally remain open circuited, but in case of ground fault path of the current would be completed through the fault and the d.c. would actuate a relay which in turn would operate a breaker. A simple static overvoltage relay has been designed and developed in the laboratory to provide protection against hazardous voltage gradients.

Before implication of the scheme to the rural area, load existing in that area needs a thorough investigation. The use of the single phase system however seems to be handicapped because of non-availability of indegenous single phase motors of rating more than 2-3 H.P. The practical possibility of operating 3-phase induction motor, with proper phase conversion unit, on single phase supply is discussed in detail. A cost comparison of 3-phase and single phase single wire transmission has been worked out to show the savings in initial investment.

BASIC CONSIDERATIONS

2.1 THE BEHAVIOUR OF CURRENTS FLOWING IN THE EARTH

The earth is a body of three dimensions and therefore the beautiful simplicity of the linear wires by which electric currents usually are directed is lost. In the earth the current spreads out in the entire space, and it is necessary to follow their path in order to analyse their performance in the underground

2.1.1 PATH OF THE EARTH RETURN CURRENT

According to ''Rudenberg(4)'', the flow of earth return current between two electrodes occurs in form of stream lines radiating in space from the electrode. This behaviour is particularly true in case of d.c. But in case of a.c. the distribution is modified due to the inductive effect of the magnetic field, except very near the electrodes, where local resistance dominates. Further when the earth is used as a part of an alternating current circuit, the current seeks in the ground a path with minimum impedance. Hence a.c. return current through ground does not spread to as great distance as does d.c. but concentrates on path in closer proximity of the overhead line itself.

If the current carrying conductor is arranged not in straight line but irregularly, the return currents do not flow back through the shortest path between the ground electrodes; but always follow the trace of the conductor. By magnetic linkage with the conductor currents, they are attracted towards the line and cannot fringe out extensively. It indicates that ground currents do not spread out traversly through the territory infesting the earth over vast distance, but that they always follow

CHAPTER 2

BASIC CONSIDERATIONS

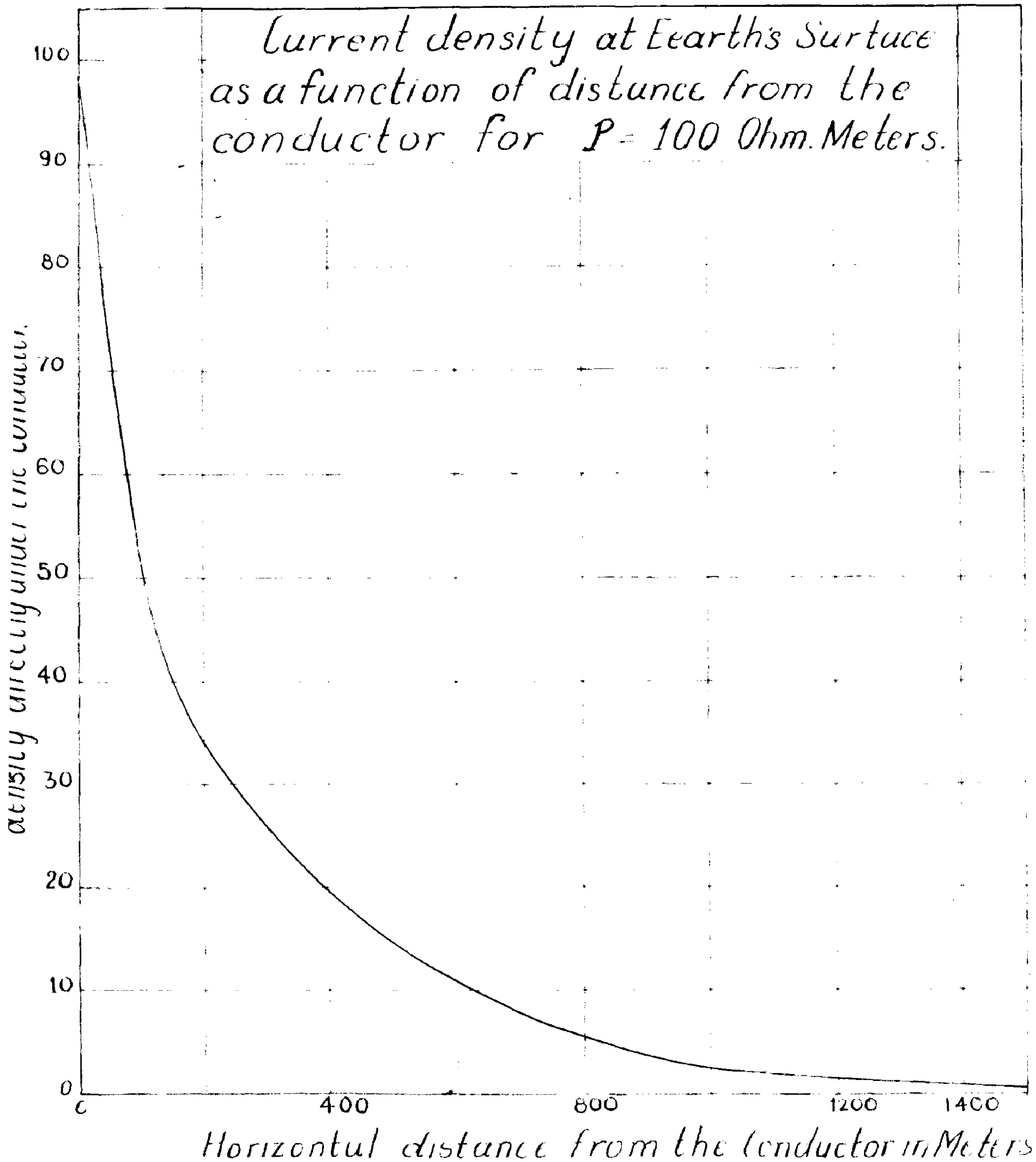
Current density at Eearth's Surface as a function of distance from the conductor for ρ = 100 Ohm. Meters.
density directly under the conductor.
100
90
80
70
60
50
40
30
20
10
0
0
400
800
1200
1400
Horizontal distance from the Conductor in Meters

Fig 2.1

the path of the transmission line with all its detours. The ground path of the current has also a finite cross section, which increases if the resistivity of the soil is decreasing or if the frequency of the current is decreasing.

2.1.2 Current Density

According to ''Rudenberg'' the current density at any point on the surface of the ground at a horizontal distance y from the conductor is given by

$$i = \frac{K^2}{2} I \, Ho \, (\sqrt{j} \; ky)^* \qquad \ldots\ldots\ldots\ldots\ldots(2.1)$$

where

I = Current in amperes carried by the conductor

Ho = Bessel function of zero order

$K = \sqrt{2\pi x 10^{-7} w}$

ρ = Resistivity of the earth in ohm meters.

$w = 2\pi f$

The amplitude of the current density, as given by equation (2.1) is plotted as shown in figure 2.1. It is evident from the figure that the current density at the earth's surface is maximum just underneath the power line and goes on decreasing as the distance from the power line increases.

2.2 IMPEDANCE OF EARTH RETURN PATH

The problem has been considered by many investigators and a number of different solutions are available which, however, usually give similar numerical results for earth impedance. Since a consideration of each of these in detail would be too lengthy, it has been decided to give one in detail, that due to

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*See Appendix I.

''Rudenberg'' which have been found to be reasonably accurate and the methods due to the others are bsiefly indicated.

For determining resistance and reactance of the ground return path ''Rudenberg'' assumes:

(1) the conductor to be placed at the centre of a hollowed cylindrical depression in the earth surface of radius equal to the height of the conductor above ground.

(2) the earth has uniform resistivity.

2.2.1 Resistance of earth return Path

According to ''Rudenberg'' the effective resistance of the ground return current path is given by

$$R = \pi^2 f \times 10^{-4} \text{ ohms/kilometer}^* \text{ ------- } (2.2)$$

It is interesting to note that the resistance of the earth return path is independant of the resistivity of the earth. This paradox is explained by the fact that at high resistivity the current spreads out over a large area and at low resistivity is restricted to an area near to the conductor.

Table - I

Frequency, f	25	50	150	cps.
Ground Resistance, R	0.025	0.05	0.15	Ohm/Km.
Diameter of return conductor, d	3.01	2.13	1.23	Cms.
Depth of return Path, D	1130	800	460	Meters.

Table I gives the return paths resistance R in ohms

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*See Appendix I.

per kilometer for various frequencies; and the diameter of a copper wire is indicated, which has the same resistance as the ground return. Hence the ground replaces for power currents of 50 cps., a return conductor of about 20 mm. in diameter.

2.2.2 Reactance of the earth return path

In addition to the resistance, the ground currents experience a substantial self inductance. According to "Rudenberg" the self inductance of the earth return path is given by *

$$L = 2 \times \log_e \left(\frac{0.178}{h} \sqrt{\frac{\rho \times 10^{-7}}{f}} \right) \times 10^{-7} \quad \text{Henries/m.} \quad \ldots (2.3)$$

where h = height of the conductor above the ground.
For h = 10 meters. = 100 ohm meters and f = 50 c/s
the reactance of the ground return path works out to be nearly 0.28 ohm/km.

The self inductance as given by the above equation, is proportional to length of the line, depends slightly on the height of the conductor above the ground and to an even lesser degree on resistivity and frequency, these being under the logarithm of a square root. The self inductance of a fictitious conductor of diameter, d, and depth, D, under the surface, the ohmic and inductive effect of which may be taken equivalent to those of ground return can be calculated. By comparison of the above equation with the self inductance of such an ideal return system, the equivalent depth can be calculated. The values of the equivalent depth, D, are shown in last row of the Table- I.

2.2.3 Theoritical work of other investigators

Bresig's Theory

"Bresig" (5) uses the method of the energy of the

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* See Appendix I.

magnetic field to deduce self inductance and mutual inductance coefficient of an earth return. He considers the conductor as surrounded on all sides by the earth, but the conductor taken as of finite length. The inductance so calculated should be too low on account of the overestimate of the accumulation of the aerical field by the assumption of earth on all sides.

Pollaczek's Theory(5)

He makes somewhat the same assumption as ''Rudenberg'' but takes the earth as a semi-infinite solid and the wire parallel to the surface and applies boundry conditions. He assumes that the electric force and current flow are parallel to wire and uniform, and that the height of the line is small compared with other quantities. He obtains a Bessels differential equation, as ''Rudenberg'', but develops some of the formulae by means of series integrals.

Mayr's Theory

He deals only with mutual inductance of earth currents, not self inductance. He assumes that the earth is a conducting stratum 300-500 meters in thickness, with a perfect dielectric of unit permeability and specific inductive capacity above and below.

Carson's Theory

He obtains a solution by means of periodic functions and Fourier integrals. With ''Rudenberg'' and ''Pollaczek'' he assumes that the electric force is parallel to the line conductor and that the earth is a semi-infinite solid with finite conductivity He determines the unknown functions by means of the conditions that at the surface of the earth both the magnetic field due to line and due to earth currents are continuous. His treatment differs from ''Pollaczek'' only in the form of functions used.

Each of these investigators has considered the surrounding medium (the earth) to be homogeneous and of uniform finite conductivity. The permeability of the earth and air is taken as unity, and dielectric constants are not taken into account.

2.3 EARTH RESISTANCE

For the transfer of power through the earth, it is necessary to have ground electrodes, at each end of the line, through which the current is conveyed to the earth. The resistance of the grounding electrodes constitutes the major part of the total resistance. As a matter of fact when we measure the earth resistance of an earth-electrode by the usual method of an earth-tester we actually measure:

(1) The resistance of the conductor connecting the earth electrode to the system.

(2) The contact resistance between the surface of the electrode and the main body of the earth.

(3) The resistance of the body of earth immediately surrounding the electrode.

The resistance of the conductor is a normal conductor resistance and can be dealth with separately. The contact resistanc has been found to be negligibly small, and the main part of any electrode resistance is that of the body of the earth surrounding the electrode.

2.3.1 General Earth Electrode

In order to examine the nature of an earth resistance, consider the simple form of an electrode i.e. a hemispherical

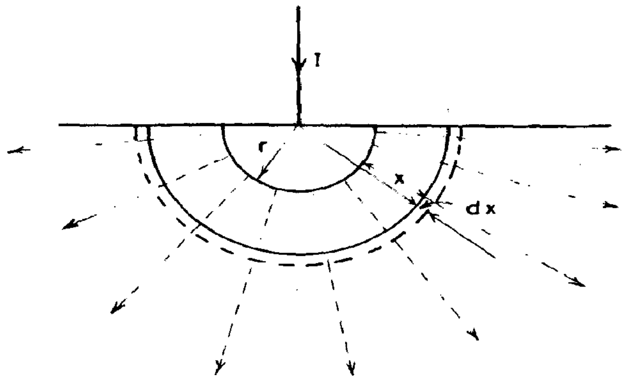


FIG.22 HEMISPHERICAL ELECTRODE

electrode. Suppose a current I is flowing into the earth through the hemispherical electrode. It will flow away in all directions and, if the return electrode is long way away, it will flow in all directions. So it can be considered that the current is flowing in a series of concentric spherical shells of which one is shown in the Fig. 2.2 These shells are all in series and, as the distance from the electrode is increased, the total resistance is increased but the cross-section of the shell is increasing, so that the elements of increase in resistance becomes gradually less.

If an individual shell at a radius x, has a thickness of dx, then the resistance of dR of the element is

$$dR = \frac{dx}{2\pi x^2} \quad \text{------} \quad (2.4)$$

and the total resistance upto a distance r, is

$$R = \int_{r}^{r_1} \frac{\rho\, dx}{2\pi x^2} = \frac{\rho}{2\pi}\left(\frac{1}{r} - \frac{1}{r_1}\right) \quad \text{....} \quad (2.5)$$

the total resistance, i.e. the resistance upto $r_1 = \infty$ is

$$R = \frac{\rho}{2\pi r} \quad \text{-----} \quad (2.6)$$

From the above equation it is evident that the resistivity of the soil is one factor, which mainly contributes to the resistance of the electrode and the size and shape are also important.

2.32. Earth- Resistivity

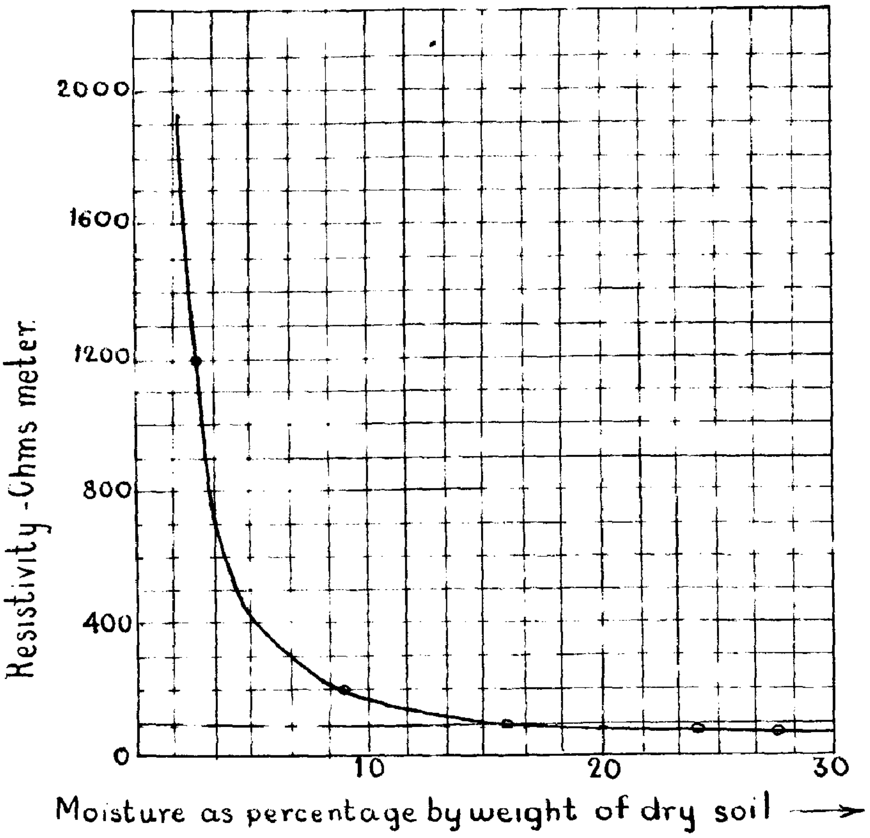
The electrical properties of the soil in themselves are of interest and important, particularly, the specific resistivity.Earth resistivity is generally expressed in ohm meters. The resistivity of a particular material, expressed in terms of this unit, is equal to the resistance in ohms between opposite faces of a one meter cubic of that material.

The electric conductivity of the material constituting the earth surface is very low, compared with, the high conductivity of the metals. Two main constituents of the earth are Silicon oxide and Aluminium oxide. Actually both of them are excellent insulators. On the other hand, even a semiconductor may carry a considerable amount of current if only the cross section is large enough and in this respect the earth by its great depth presents no limitation. The main factors which determine the resistivity of the soil are :

(1) the composition of soil i.e. geological strata.
(2) the moisture content in the soil.
(3) the temperature of the soil.
(4) the mechanical composition of soil.

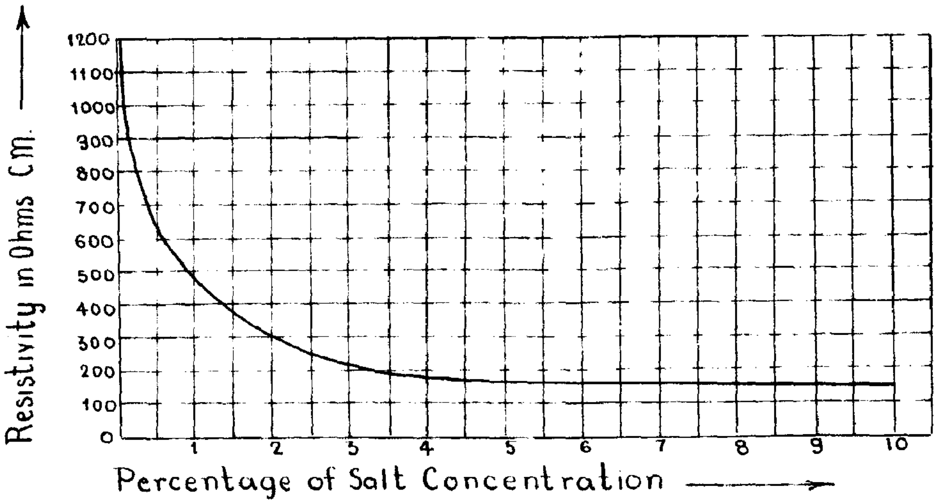
2.3.2.1 Effect of the type of soil

The type of soil is very important in determining the earth resistivity (7). Attempts have been made to co-relate the resistivity with the geological age of the strata (8). Although olden materials in general has higher resistivity, many exceptions were found. In the actual strata under the



VARIATION IN SOIL RESISTIVITY WITH MOISTURE CONTENT.

Fig 2.3



VARIATION OF SOIL RESISTIVITY WITH SALT CONCENTRATION

Fig. 2·4.

surface, loam, clay and lime stone usually have lower resistivity, sandy and rocky material have higher resistivity.

Some typical values of resistivity of some soils are :

TABLE II

Type of Soil	Resistivity in ohm m.
Loam, garden soils etc.	5 - 50
Clay	8 - 50
Hard Clay	50 -150
Chalk	90 -140
Marsh	2.2 -2.7
Clay, sand and gravel mixtures	40 -250
Sand and Gravel	60 -100
Slates, Shale, Sand Stone etc.	100 -500
Crystaline rocks	200 -10000

2.3.2.3 The Moisture Content of the Soil

The amount of water present in the soil is a major factor in determining the earth-resistivity.Experiments have proved (7), that even a trace of moisture in a sample of dry soil has a considerable effect in reducing the soil resistance. The manner in which the resistivity of soil varies with the moisture content is illustrated in Fig. 2.3. It will be notified that the resistivity at first, falls rapidly as moisture content is increased but after a value of 14 -15 per cent the rate of decrease becomes much less.

2.3.2.3 Effect of Salt Concentration

As a matter of fact, the water alone without the

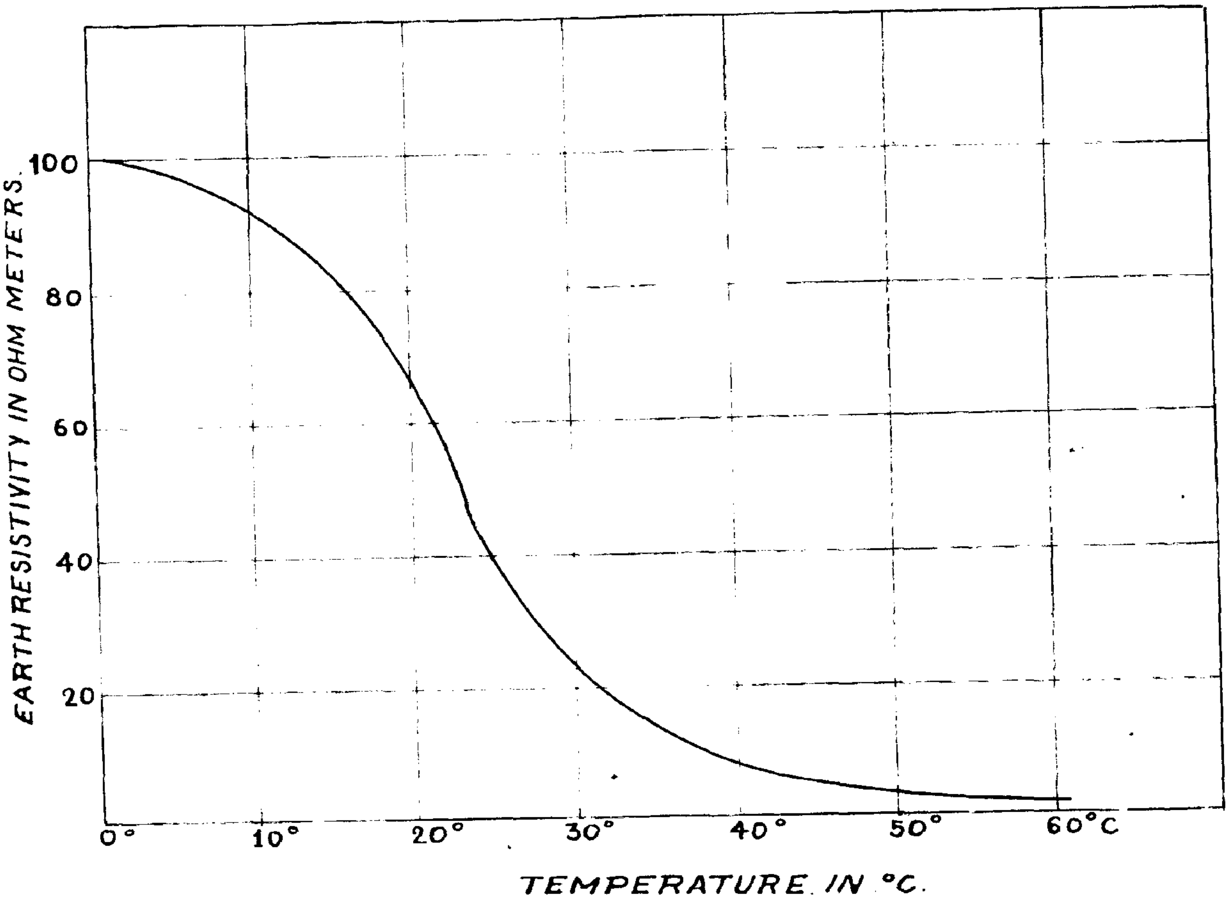

VARIATION OF RESISTIVITY WITH TEMPERATURE.

FIG 2.5

presence of salt is a poor conductor.The resistivity of the water and that of soil is governed by the amount of salts dissolved in it. (Fig.2.4).

From the figure it can be seen that the resistivity of the soil decreases with added salt concentration.

2.32.4 Effect of Temperature

The temperature of the soil has an appreciable effect on resistivity especially when temperature falls below freezing point. Fig. 2.5 indicates that the resistance increases sharply as the temperature goes down, but smooths out as the temperature rises.

2.32.5 Mechanical Composition of Soil

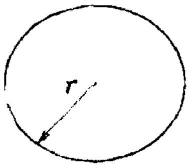
Figures are not available to show the effect of the mechanical composition of the soil in neighbourhood of the electrodes; but in general the finer the grading, lower will be the resistance. Course grading does not provide for the retention of the same amount of moisture as is possible with finer materials, and this probably accounts for the high resistivity.

2.32.6 Variation of Resistivity with Seasons and Locations

Seasonal variations also affect the soil resistivity a lot, firstly due to temperature variations and secondly due to rain i.e. increase in moisture content of the soil. During the rains the soil resistance is very small.It is not possible to allocate a definite value of resistivity to a given type of

TABLE III

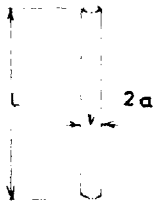
SPHERE



$$R = \frac{\rho}{4\pi r} \text{ ohms} \quad \cdots \quad (2\cdot7)$$

ρ = RESISTIVITY OF THE EARTH IN ohms
r = RADIUS OF THE SPHERE IN meters

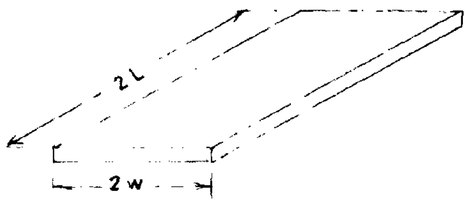
ROD



$$R = \frac{\rho}{2\pi L}\left[\log_e \frac{4L}{a} - 1\right] \text{ohms} \quad \cdots \quad (2\cdot8)$$

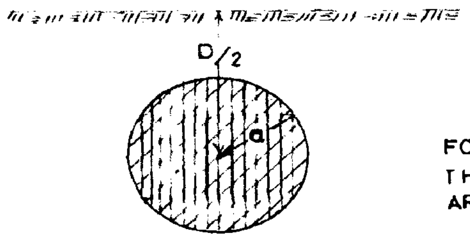
ALL DIMENSIONS ARE IN meters

STRIP



$$R = \frac{\rho}{4\pi L}\log_e\left(\frac{4L}{w}\right) \quad \cdots \quad (2\cdot9)$$

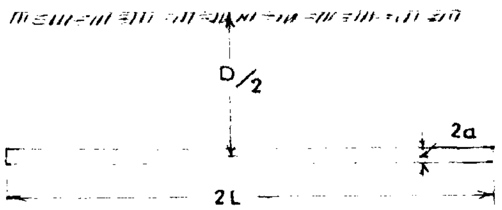
PLATE ELECTRODE



$$R = \frac{\rho}{8a} + \frac{\rho}{4\pi D} \quad \cdots \quad (2\cdot10)$$

FOR SQUARE VERTICAL PLATE THE RESISTANCE IS THE SAME AS FOR ROUND PLATE OF THE SAME AREA

BURIED STRAIGHT HORIZONTAL WIRE



$$R = \frac{\rho}{4\pi L}\left[\log_e \frac{4L}{a} + \log_e \frac{4L}{D} + 2 + \frac{D}{2L} - \frac{D^3}{16L^3}\right] \quad \cdots \quad (2\cdot11)$$

EARTH RESISTANCE OF GROUND ELECTRODES

soil, as this varies with the location in which the soil is found. Furthermore the resistivity can change very rapidly with location, due partly to change of moisture content and partly to change in type of soil.

2.3.3 CRITICAL REVIEW OF THE DIFFERENT GROUNDING ARRANGEMENTS.

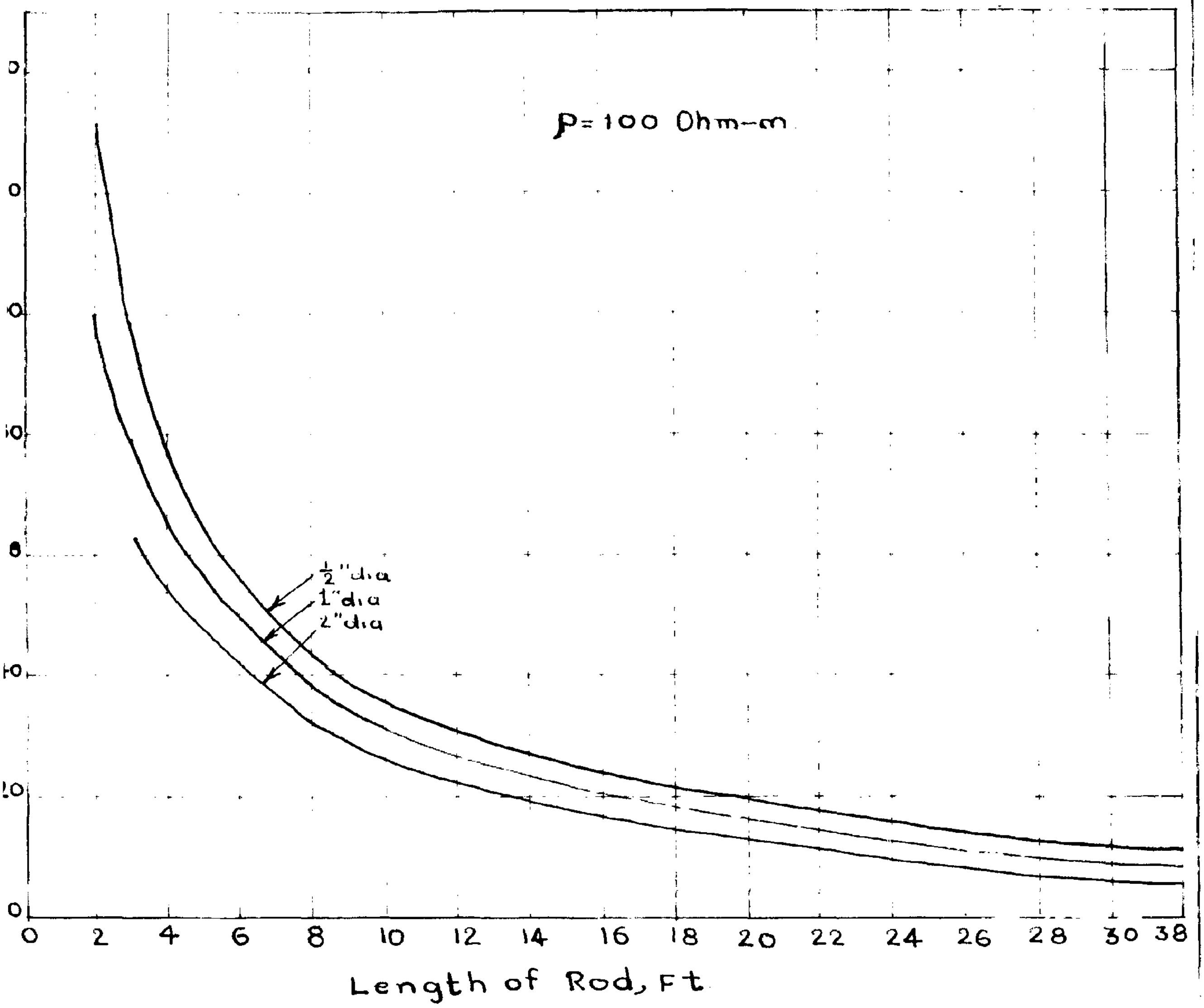
Effective ground connection is the key to the successful operation of earth return for continuous flow of the current. And selection of the proper grounding electrodes is of prime importance to provide the effective ground connection.

The earth-electrodes which are generally used for grounding are :

(1) Driven rods or pipes
(2) Plate Electrodes
(3) Strips
(4) Buried Straight horizontal Wires.

2.3.3.1 Driven Rods or Pipes

From the practical view point, where conditions are satisfactory, the most suitable form of electrode is the driven rod or pipe. The resistance of a single driven rod or pipe is given in the Table III. Curves calculated from the equation for the resistance of single driven rod given in Table III are given in Fig.2.6. For rods of different diameters and for a specific resistance of 100 ohm-meters. These curves show that an increase in length has a much greater effect.The best length of rod to use is determined by the nature of the



RESISTANCE OF DRIVEN ROD ELECTRODE. FIG 2.6.

soil among other factors. If for instance, specific resistance tests indicate that there is an underlying stratum of lower resistivity a rod long enough to reach this should be used, so that benefit of lower resistivity can be obtained.

The practical advantages of driven rods over other forms of electrode may be summarised as follows:-

1) The low cost of driven rods when compared with other electrodes.
2) Where the surface soil is sandy, or where the permanent moisture is at a considerable depth, rods can be driven to much a depth as will result in too much reduction in resistance.
3) Seasonal variations are very much less with deep rods than with buried electrodes as such rods will be unaffected by drying out of the soil in summer or freezing in winter.
4) If artificial treatment with a salt solution is considered necessary, the process is simpler with earth rods than with any other electrode.
5) Quite a number of electrodes can be driven for the cost of single earth plate, giving for the same cost much lower earth-resistance.
6) The connexion between the earth-rod and the conductor to which it is coupled can be quite simple and can be easily inspected and where necessary can be replaced.

2.3.32. Plate Electrode:

The second type of earth electrode is the

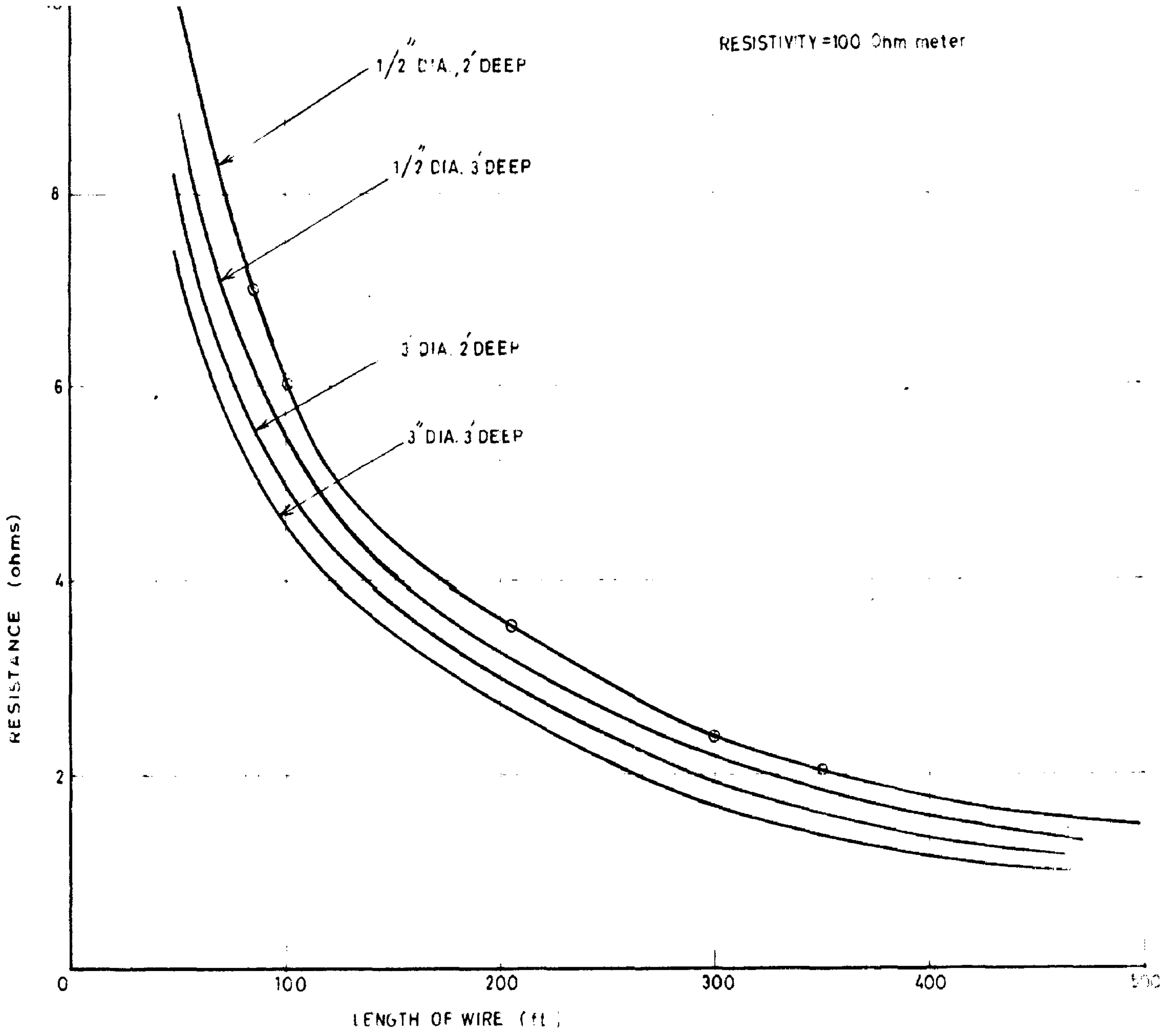


FIG.2.7 RESISTANCE OF BURIED HORIZONTAL WIRE

burid plate.This was the earliest form of earth electrode to be used.In the past considerable use has been made of buried plates of 3' x 3' .The resistance to earth of the buried vertical plate is indicated in Table III.

Earth plates, due to the following draw-backs, are being possibly replaced by driven rods.

1) Cost of burying the plate is high.
2) The connection between the earth plate and the conductor to which it is connected cannot be quite easily inspected,and is also susceptible to corrosion.
3) Seasonal variations are much as compared to the driven rods.

2.3.3.3 Strip Electrode:

These electrodes,if in the form of strips are usually made from copper having section not less than $1'' \times \frac{1''}{16}$ which is preferably untined.

2.3.3.4 Buried Straight Horizontal Wire:

In many situations,where it is desirable to obtain a ground of low resistance,it may be convenient to install a buried wire ground either by ploughing or hand trenching. Especially where rock is present under the surface,the only solution is to use a horizontal wire buried at the required depth. Curves calculated from the equation for the resistance of buried horizontal wire given in Table III are shown in fig.2.7. These curves show that the depth of burial has little effect on resistance.It is necessary to bury only deep enough to prevent theft.

2.3.3.5 Ground Electrode Material

Copper is by far the most common metal used for ground grid conductors, at least in the United States.(15) Copper and steel is usually used for grounding rods.Copper in addition to its high conductivity, has the advantage of freedom from under-ground corrosion, since it is cathodic with respect to other metals likely to be buried in the vicinity.

But in our country use of copper electrodes is a costly affair due to shortage of the metal.Many utilities have reported the successful use of steel as material for ground rods and ground grid conductors. But it often requires some form of cathodic protection often in combination with galvanizing of the steel or use of corrosion resistant steel.

Less frequently, aluminium has been used for grounding electrode.In such cases the relativity high purity electric conductor grade is more satisfactory than most alloys. Use of aluminium, like use of steel avoids contributing to the corrosion of the underground pipes etc. However, the aluminium itself may corrode in certain soils. Alternating current corrosion of aluminium may also be a problem under some conditions. Hence, aluminium should be used after full investigations of the problem,however, it is beyond the scope of the dissertation topic.

2.3.4 Voltage drop in the ground

Assuming a single driven rod is used as ground electrode the voltage drop in the ground can be calculated as follows :-

For a length of ground rod- 10' diameter 1" and earth resistivity = 100 ohm. meter, the resistance due to ground electrode = 31 ohms. Let us take the length of the line as 1 Kilometer, then earth resistance per kilometer from Table 1 = 0.05 ohms. Earth reactance per kilometer =0.286 ohm. It can be seen that the resistance of ground is far greater than the impedance of the earth path.

Total impedance = 31 + 0.05 + j0.285

= 31 ohms.

For a current of 10 ampheres, the voltage drop is

v = 31 x 10 = 310 volts.

Hence for proving the voltage regulation, the transmission voltage would have to be stepped up. However, the voltage drop in the ground can be substantially reduced by reducing the earth resistance which is the root cause for the excessive voltage drop.

2.4 THE GRADIENT PROBLEM

One of the natural effects of current flow through earth electrode is that a voltage gradient is present on the surface of the earth in neighbourhood of the electrode. The fundamental reason for this gradient is that the resistance of the electrode is not concentrated at one point but is distributed over the soil in its vicinity. However, the resistance of an earth electrode is not in itself sufficient to characterize the performance. It only defines the overall potential $U_o = RI$ which the passage of current I produced in an electrode in relation to earth at a greater distance. The potential U_o is the integral of all the elemental increases which are met with when following any path from infinity to the electrode. Practical interest attaches to the potential between specific points along this path which may not be the electrode and infinity. In order to characterise the electrode completely it is necessary in practice to know the distribution or the 'map' of the potential throughout the whole of the surrounding ground, taking into account its natural and artificial lack of homogeneity.

2.4.1 The simplest possible electrode is a sphere in the ground which is symmetrical in all directions. It may be imbeded in the ground or only the lower hemisphere. If a current I flows through the hemisphere then the current density at distance x from the centre of the electrode is given by

$$J = \frac{I}{2\pi x^2}$$

This produces an electric field strength in the soil equal to

$$e = \frac{\rho I}{2\pi x^2} \qquad \text{------ (2.11a).}$$

From this equation it can be seen that a considerable potential difference exists over a relatively short distance near the earth electrode.

2.4.2 DANGER TO HUMAN BEINGS AND ANIMALS

If a human being or animal is walking through such a surface field of electric potential, the body diverts some current from the earth and this may be sufficient to result in fatality. Actually this factor is rather a difficult to analyse, as the danger to living being depends on many circumstances. The pathway that the current traverses in its passage, is of extreme importance in determining the magnitude of the shock hazard. If there are such vital organ as the brain the heart or lungs in the current path even very small currents result in fatalities. If there are no vital organs in the current path the resulting injury is less. A very common case is the flow of current between limbs (hand to hand or hand to foot in the case of human beings) so that an important part of the current passes the heart. Moreover the shock hazard depends on the current magnitude, duration, wave form; frequency and phase of heart cycle at the instant of shock. The last decade and half have seen considerable work done all over the world on the electric shock hazard. The following data, has been given by several authorities(10,11,12) regarding the physiological effects of shock in order of rising current flow at 50 c/s.

1 mA can be perceived

10 mA are painful, with a somewhat greater current it becomes impossible to let go a firmly grasped electrod

Unconsciousness may occur at 40 mA.

100 mA may give rise to a fatal accident if it permits

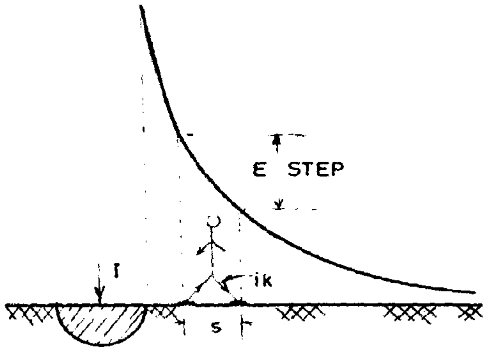
for one second or more - the regular functioning of heart is disturbed, fibrillation starts and does not recover by itself. A current of shorter duration produces fibrillation only if it conicides with an appropriate phase of the heart cycle. One or more amperes are less dangerous if applied for a very short period only - the fibrillation is cured immediately after it starts, with longer duration, external and even internal burns may occur. If the current passes the centre of respiration (at the base of the brain) the respiration may be disturbed.

Direct current is a little dangerous than 50 c/s alternating current.

High frequency current is practically harmless apart from the possibility of burns.

A current just below the threshold for ventricular fibrillation is the maximum to which man safely may be subjected. Based upon numerous tests on animals of several species comparable in size with man, this maximum current is about 0.1 amp at 50 c/s. The resistance of the human body is difficult to determine since it varies from person to person. Body resistance can range from few hundred to several thousands of ohms. For all practical purpose the body resistance is taken as 1000 ohms on an average. Dry skin is a good insulator, but does not withstand high voltages. With low contact resistance (e.g. wet hands, wet shoes) less than 100 volts may cause death.

However, for all purpose of ascertaining the maximum voltage that can be withstood by a living being, 0.1 amp. is taken as the maximum tolerable current.



POTENTIAL AT THE SURFACE OF THE EARTH NEAR
A CURRENT CARRYING ELECTRODE

FIG 2·8

2.4.2.1 Step Voltage

The electrid field strength produced in the soil due to current flow through the hemispherical earth electrode, as given by equation 2.11, is plotted in Fig. 2.8. When a person is walking on such a surface field of electric potential, potential difference E step is shunted between two feet as shown : The current resulting from step voltage enters the body via one foot and passes out through the other and may cause serious damage This step voltage is given by the line integral of the electric field strength over the width S. This is with the use of equation 2.11.

$$E_s = \int_{x}^{x+s} e \; dx \qquad \text{..........(2.12)}$$

$$= \frac{\rho I}{2\pi} \int_{x}^{x+s} \frac{dx}{x^2}$$

$$= \frac{\rho I}{2\pi} \quad \frac{s}{X(x+s)} \qquad \text{........(2.13)}$$

At a distance x from the electrode, large compared with the step width,

$$Es = \frac{\rho IS}{2\pi x^2} \qquad \text{.................(2.14)}$$

decreases inversely to the square of the distance. In proximity to the electrode, the step voltage will rise to a maximum as given for $x = D/2$ by

$$Es = \frac{2}{\pi} \cdot \frac{S}{D(D+2S)} \rho I \qquad \text{......(2.15)}$$

Where D = Diameter of the electrode.

Thus the step voltage depends not only on the ground current and the distance from the electrode, but also on step width and resistivity of the ground, and increases with both these values.

Actually the danger to living creature is not dependent on the voltage but on the current flowing through body. This current depends substantially on the resistance of the body itself, the magnitude of which is highly variably. The maximum possible current develops if the internal body resistance is small compared with foot resistance on the ground. The foot resistance is

$$r = \frac{\rho}{2\pi b} \qquad \text{..........(2.16)}$$

where b is the equivalent radius of the creatures foot.

2.4.2.2 Safe step voltage for human beings.

For a human being the equivalent radius of foot is usually 7 cms. on an average. The voltage drop by the body current through the resistance 2r due to both feet is given by the voltage taken over the step width S then the step voltage is

$$E_s = 2r\ i_k^{(13)} \qquad \text{..............(2.17)}$$

Where i_k is the body current from 2.17

$$i_k = \frac{Es}{2\ r} \qquad \ldots\ldots\ldots\ldots\ldots \ (2.18)$$

Neglecting the body resistance, which gives the worst condition from (2.16)

$$i_k = \frac{\pi b\ Es}{\rho} \qquad \ldots\ldots\ldots\ldots\ldots \ (2.19)$$

As has been seen already, the maximum fibrillation current is taken as 0.1 ampere at 50 c/s. Hence if $i_k = 0.1$

$$Es = \frac{0.1\ \rho}{\pi b} \qquad \ldots\ldots\ldots\ldots\ldots \ (2.20)$$

For a value of earth resistivity = 100 ohm m and b = 7 cms.

$$Es = 46 \text{ volts}$$

Thus the voltage difference between the two feet of a man should not be more than 46 volts. For other soil resistivities the voltage is directly proportional to the resistivity.

2.4.2.3 Safe step voltage for animals

In case of animals, step voltage is the potential difference shunted between the fore and hind legs. The path of the current due to step voltage for an animal involves vital organs such as heart and lungs and relatively small magnitude of current may result in fatality.

For animals step voltage Es is given as

$$Es = \frac{0.1\rho}{2\pi b} \qquad \ldots\ldots\ldots\ldots\ldots \ (2.21)$$

Assuming the average radius of foot of animal as 4 cm and earth resistivity = 100 ohm.m.

$$Es = \frac{0.1 \times 10000}{2\pi \times 4} = 40 \text{ volts.}$$

2.4.2.4 Touch Voltage

Touch voltage is the potential difference shunted between

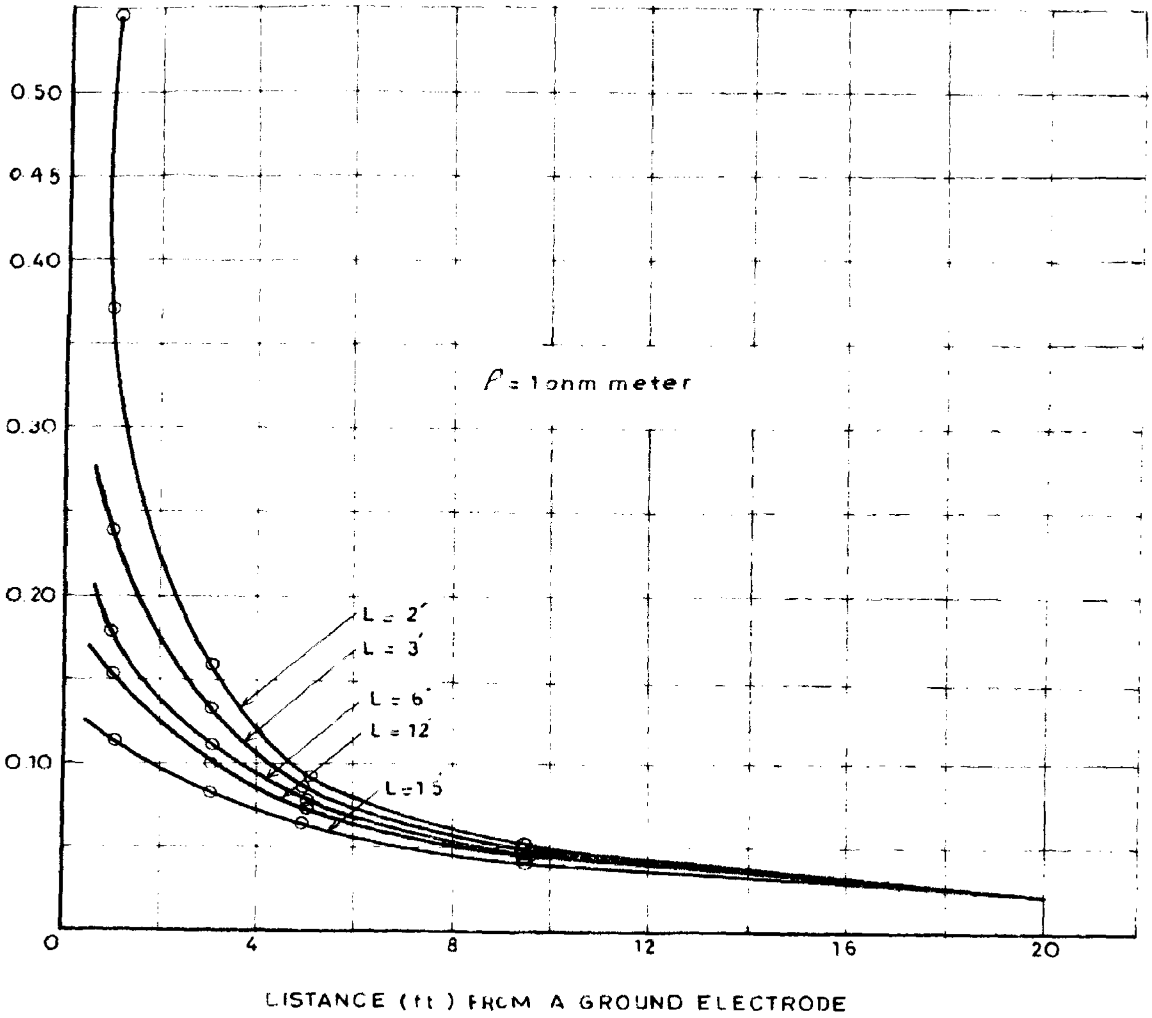


FIG.29 POTENTIAL NEAR A GROUND ELECTRODE

one hand and the feet. It is denoted by Etouch. In general this is the potential difference between the ground electrode and points on the ground one meter distant. The path of the current due to touch voltage involves such vital organis as heart and lungs. Many fatalities of operating personnel haveq occurred due to touch contact. In this case about half the resistance of a single foot is effective and Etouch = $\frac{0.1\rho}{2\pi b}$ = 23 volts.

2.4.3 DETERMINATION OF POTENTIAL GRADIENTS

In order to find out the step and touch voltages, the potential distribution has to be determined. The potential gradient in the vicinity of ground electrode can be determined by

Analytical Methods.
Model tests.
Field Tests.

2.4.3.1 Analytical Method

It is possible to compute potential gradients for simple electrodes in homogenous soil analytically.

Potential gradient in the vicinity of driven rod.

The earth potential in volts at the surface of distance y cm. from a vertical ground rod or pipe of length L is given by

$$V(y) = \frac{I\,P}{2\pi L}\ \mathrm{Sin\,h}^{-1}\ L/y \qquad \ldots\ (2.22)$$

(14)

$$= \frac{I}{2\pi L}\ \mathrm{Log}_e\ \frac{2L}{y} \quad \text{when}\quad y < L \qquad \ldots\ (2.23)$$

$$= \frac{I}{2\pi y} \quad \text{when}\quad y > L \qquad \ldots\ (2.24)$$

Fig. 2.1 shows the curves which indicate the variation of earth potential as calculated from the above equations, with the distance from the electrode, for various lengths of the electrode.

Potential gradient in the vicinity of buried horizontal wire

For a wire of length 'L' buried at depth d the potential at a point on the surface at horizontal distance 'y' from wire and a longitudinal distance 'x' from a line through the midpoint of the wire is given by (14)

$$V\ (x,y) = \frac{I\rho}{2\pi L} \cdot \text{Log} \frac{\left[(x+L/2)^2 + y^2 + d^2\right]^{\frac{1}{2}} + x + L/2}{\left[(x-L/2)^2 + y^2 + d^2\right]^{\frac{1}{2}} + x - L/2} \quad \ldots(2.25)$$

$$V\ (o,y) = \frac{I\rho}{\pi L}\ \text{Log} \frac{\left[(L/2)^2 + y^2 + d^2\right] + L/2}{(y^2 + d^2)^{\frac{1}{2}}} \quad \ldots(2.26)$$

$$V\ (o,o) = \frac{I\rho}{\pi L}\ \text{Log} \frac{\left[(L/2)^2 + d^2\right]^{\frac{1}{2}} + L/2}{d} \quad \ldots(2.27)$$

$$\cong \frac{I\rho}{\pi L}\ \text{Log}\ \frac{L}{d} \quad \text{when} \quad d << L$$

The maximum earth potential equals V(o,o)
In the above derivations earth resistivity is assumed to be uniform throughout the surface.

When there are number of rods or wires then the resultant earth potential is obtained as the sum of earth potential due to each, the current in each of equal rods or wires being taken as I/n.

2.4.3.1.1 Drawbacks of Analytical Method

In analytical method the caluculations become unduly complicated for any practical grounding arrangement. Any calculated value is a good approximation due to non rigorous method and analytically the effect of varying the different parameters of grounding arrangement. By analytical method it is difficult to arrive at optimum ground electrode arrangement which will be most economical and suitable electrically. Also the resistivity of the soil throughout the different parts of current varies over a considerable range. The variation cannot be readily considered in the mathematical analysis and to that extent the accuracy is limited.

2.4.3.2 Model Tests

Scale model tests can be employed to determine ground resistance and potential gradient pattern of any grounding arrangement. This method is discussed in detail in Chapter 3.1.

2.4.3.3 Field Tests

The voltage gradients can be determined by conducting the actual field tests. This method will be discussed in detail in Chapter 3.2.

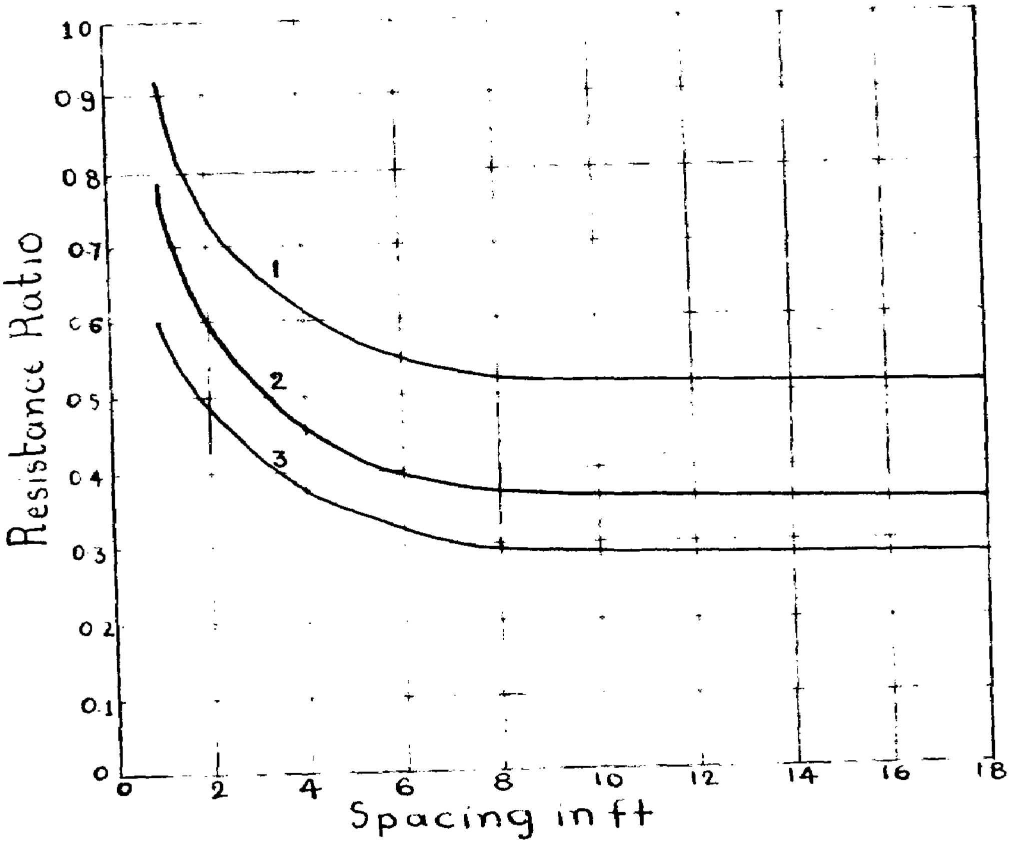
2.4.4. METHODS OF REDUCING VOLTAGE GRADIENTS

Dangerous potential gradients can be prevented by obtaining a suitable low value of earth resistance which is the root cause of these potential gradients. Low earth resistance can be obtained by -

1) Deep driven electrodes
2) Multiple electrodes
3) Horizontal Buried wires
4) Chemical treatment of the soil

Resistance Ratio = $\frac{\text{Resistance of rods in parallel}}{\text{Resistance of one rod}}$

1. Two rods in parallel
2. Three rods in triangal
3. Four rods in square



COMBINED RESISTANCE OF RODS IN PARALLEL.

Fig 2.10

2.4.4.1 Deep Driven Electrodes

For a driven electrode the resistance decreases as the length of electrode increases. From the fig. 2.6 it can be seen that the resistance to earth is considerably reduced if the depth of rod is increased to 15 feet. From a theoritical view point the most economical installation consists of single rod electrode to whatever depth is required for the resistance desired. Site conditions, however, are often unsuitable for deep driving.

2.4.4.2 MULTIPLE DRIVEN ELECTRODES

The resistance of a single driven rod is in general not sufficiently low and it is necessary to use a number of rods connected in parallel. Considerable care has to be taken when this is done as rods so connected do not necessarily comply with the usual low resistances in parallel. This is because the resistance of any one rod is contained in a body of the earth surrounding it and, if the full effect of the resistance in parallel is to be attained, the electrodes should be spaced enough away from each other so as not to overlap the resistance areas of their neighbours. In Fig. 2.10 curve 1 shows the variation of resistance of two driven pipes distant apart. It can be seen from the curve that as the distance between the electrode increases resistance decreases rapidly at first and then more slowly tending towards a value R/2 at infinite distance. Hence it becomes necessary to determine what reduction in the total resistance can be obtained by connecting rods in parallel.

This problem has been studied by many of the investigators(16), and various imperical formulae have been developed to calculate the total resistance that can be obtained by connecting rods in parallel. Instead of giving the mathematical formulae

RESISTANCE OF MULTIPLE ELECTRODES AT VARIOUS SPACINGS IN TURMS OF PERCENT RESISTANCE OF SINGLE DRIVEN ROD.

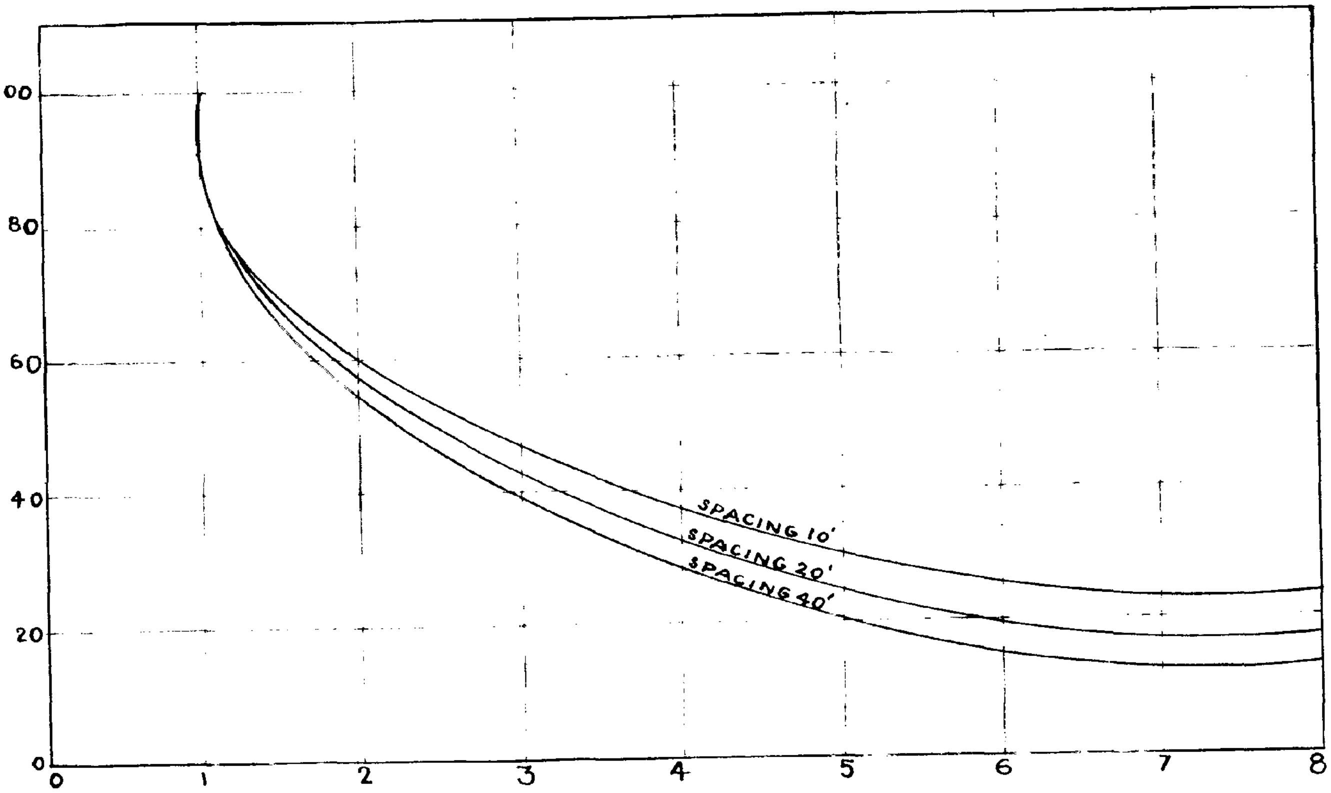
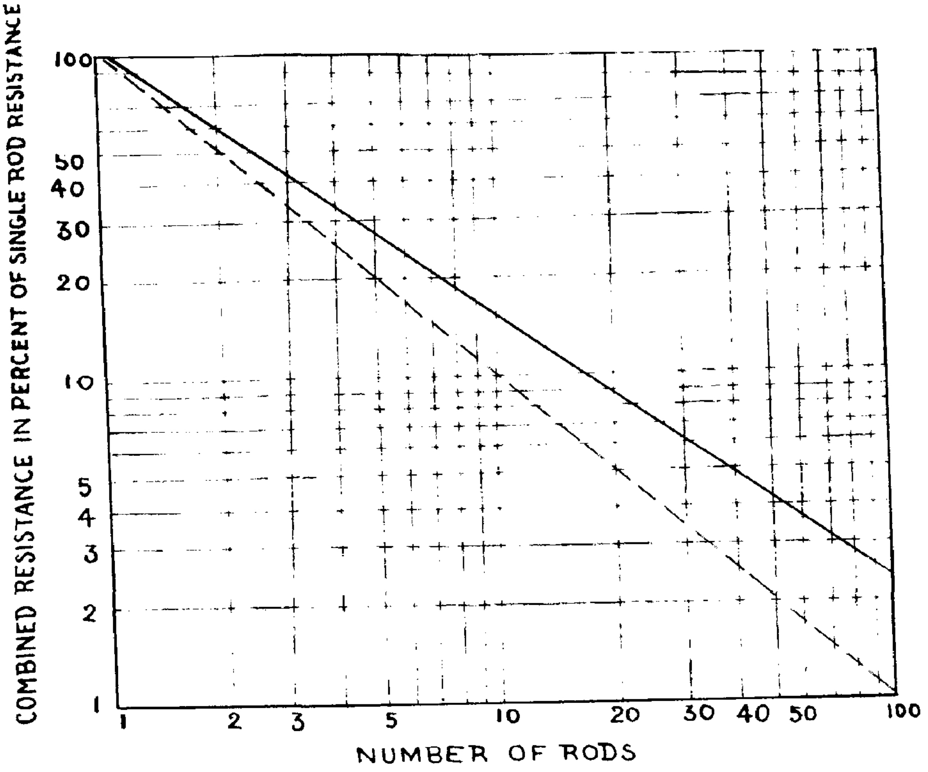


Fig. 2·11



VARIATION IN COMBINED RESISTANCE OF RODS CONECTED IN MULTIPLE WHEN ARRANGED ON A STRAIGHT LINE OR A CIRCLE WITH SPACING BETWEEN RODS EQUAL TO LENGTH OF ROD. DASHED LINE INDICATES COMBINED RESISTANCE WITHOUT MUTUAL EFFECTS. ROD LENGTH 240 TIMES ROD RADIOUS AS FOR 5 FT ROD OF $\frac{1}{2}$" DIA

Fig 2.12.

to account for the above, the curves have been prepared in this Chapter to show the characteristics of multiple driven rods for different arrangements. In Fig. 2.10 curve 2 indicates the combined resistance of 3 rods in a triangle, in parallel, curve 3 indicates combined resistance of four rods in a square, in parallel. Fig.2.11 gives the combined resistance of number of rods in percent of the resistance of single rod when they are placed at different spacing. Fig. 2.12 gives the combines resistance of rods in percent of the resistance of rods, arranged in a straight line and in a circle in parallel, when the spacing is equal to the length of the rod.

From the above figures we can directly determine the number of electrodes and spacing between them required to secure the required ground resistance.

2.4.4.3 Horizontal Buried Wires

In the areas where rock is present at 3 or 4' below the earth surface the only solution for reducing the earth resistance is the horizontal wire buried in the ground at required depth. If necessary number of buried wires connected in parallel can be used to reduce the earth resistance and the potential hazard. The characteristics of the buried horizontal wire has already been discussed in 2.3.3.4.

2.4.4.4 Chemical Treatment of Soil

Where it is not possible to obtain earth resistance low enough, the resistance of the existing electrode can be decreased by means of chemical treatment of the soil in its immediate neighbourhood.

The effect of chemical treatment may be calculated as follows.

Suppose a hemispherical electrode of radius r_1 is surrounded by a medium composed of two layers each being homogenous and hemispherical in shape, the resistivity of the inner medium being ρ_1 and its radius r_2. The resistivity of the outer being ρ_2 and being infinite in extent, then the resistance of the electrode is given by

$$R_2 = \frac{(\rho_2 - \rho_1)r_1 + \rho_1 r_2}{2\pi r_1 r_2} \text{ (17) ohms.} \quad \text{----- (2.28)}$$

Let R_1 - Resistance of the electrode without chemical solutions around it,

Then

$$\frac{R_2}{R_1} = \frac{(\rho_2 - \rho_1)r_1 + \rho_1 r_2}{\rho_2 r_2}$$

$$= \frac{\rho_1}{\rho_2}\left[1 - \frac{r_1}{r_2}\right] + \frac{r_1}{r_2} \quad \text{----- (2.29).}$$

If ρ_2 is much greater than ρ_1 the equation can be reduced to

$$\frac{R_2}{R_1} = \frac{r_1}{r_2}$$

In otherwords the treatment merely increases the effective dimensions of the electrode of the material used in treatment has low resistivity as compared with the original resistivity of the soil.

The chemicals generally used are

(1) Sodium chloride

(2) Calcium chloride

(3) Sodium Nitrate

(4) Magnesium sulphate

(5) Copper sulphate etc.

The selection of the above salt solutions to be used depends largely on cost, availability and the corrosive effect of the chemical.The salts have, of course,a tendency to be absorbed by the surrounding earth so that the reduction in resistance may not be permanent but may last a few years, and then needs retreatment. Clarke and Watkins (17) propose the use of the following chemicals for permanent reduction in earth resistance.

1. Methylenebisacrylamide (commonly known as Acrylamide)
2. Silicate gels
3. Copper Ferrocynite gels
4. Graphite and water.

The use of the above chemicals have been relatively costly.

2.4.4.5 Fencing of the Grounding System.

The grounding system should be properly enclosed by fence, to keep unauthorised person at safe distance.Wooden posts should be used for this purpose. If the metal posts are used then the buried portion of the post would be at the potential of the ground. This would be transformered to the fence above ground resulting in a considerable touch voltage.

2.5. INTERFERENCE WITH TELECOMMUNICATION LINES

The use of single phase single wire line with earth return, in close proximity to overhead telecommunication line, will result in a measure of interference with the telecommunication system by virtue of the deliberate use of the earth return path for load currents.

2.5.1 Coupling between the Power Line and Communication Line

The coupling between a power line carrying alternating current which returns through earth and the communication conductor parallel to it is of two fold nature. In the first place the communication conductor lies within the aerial field set up by the current in the line. The induction due to this field is however small, and at a distance from the power line negligible. Secondly the return current produces a potential distribution through the earth, caused not only by the resistance of the earth return path, but also by the alternating magnetic field of earth currents. Thus the e.m.f. appearing on the communication conductor will depend on its route between the two points at which it is connected to earth in relation to the path of the earth current.

2.5.2 Longitudinal Voltage induced in the Communication Line

If at a distance y meters a telecommunication line runs parallel to the transmission line with current I returning through the ground, and the two ends of the secondary line are directly or indirectly grounded, then according to ''Rudenberg''longitudinal voltage developed over a length L kilometers of this line is given by

$$e = \pi w.I\ L\ H_0\ (\sqrt{j}\ ky)\ 10^{-4} \text{ volts} \quad ----- (2.30)$$

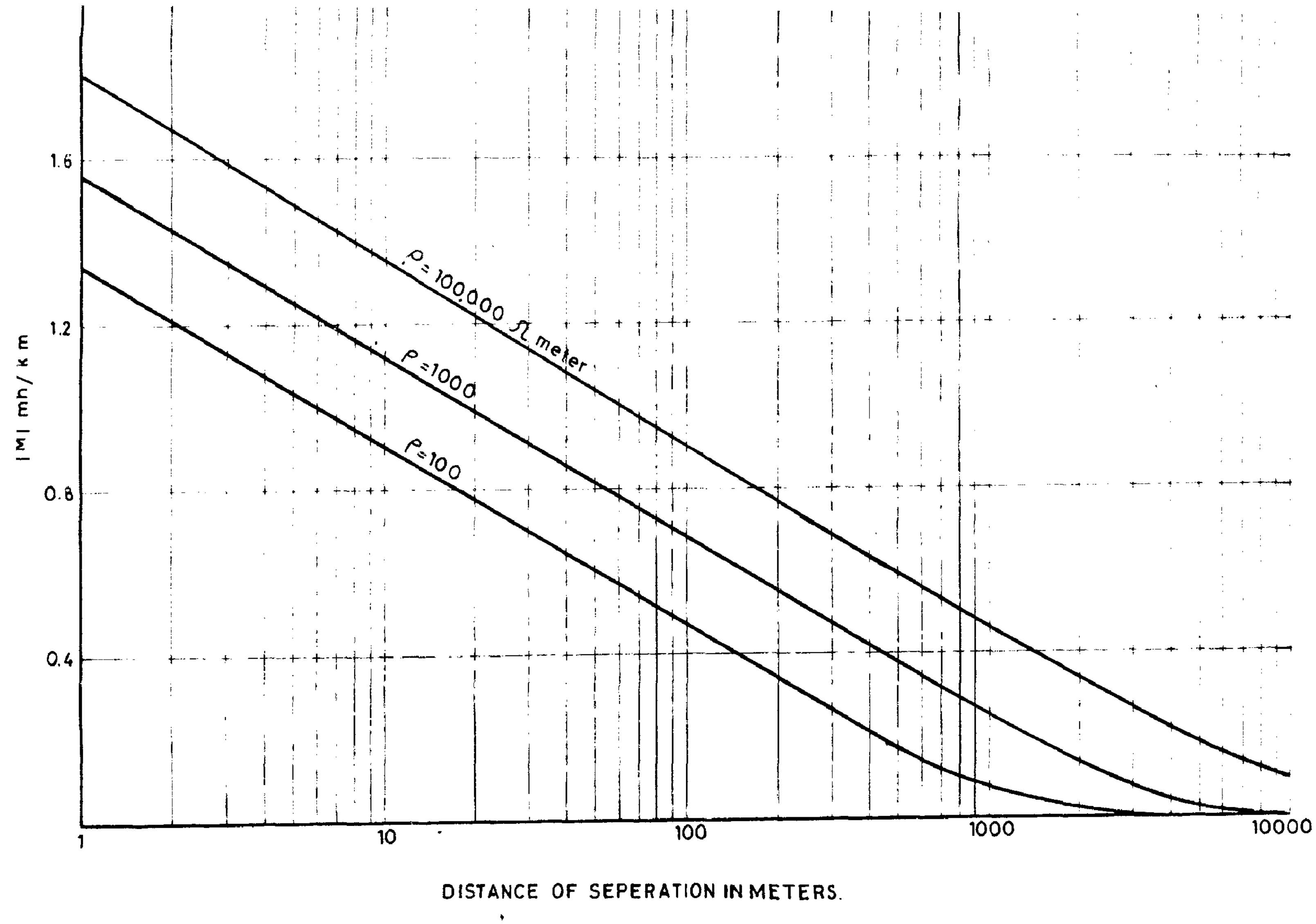


FIG.2·13 MUTUAL INDUCTANCE BETWEEN LINES WITH GROUND RETURN (f=50 c/s)

Where H_o = Bessel function of the order zero.

$$K = 2\pi \sqrt{\frac{f \times 10^{-7}}{\rho}}$$

This is a voltage of mutual effect between the two lines caused mainly by action of ground return currents and their magnetic field.

2.5.3 Coefficient of Mutual Induction

Following the concept of mutual induction, we can express the amplitude of the induced voltages as

$$e = w\, m\, L\, I \quad ------ (2.31)$$

Where m - Mutual inductance per meter length of the line.
Thus we obtain from Eq.(2.30) as mutual inductance per kilometer length.

$$m = \pi H_o (\sqrt{j}ky) \times 10^{-4} \quad \text{Henries} \quad ----- (2.32)$$

The value of m depends not only on the geometric position and form of the two circuits, but also on the frequency of the alternating current and the resistivity of the ground. For moist soil of resistivity ρ = 100 ohmm for dry soil ρ = 1000 ohm and for bedrock of ρ = 100,00 ohm m, the mutual inductance on of Eq. (2.32) is plotted in Fig.2.13 against distance, the latter being shown in meters for frequency of 50 c/s. The units are given in millihenries per kolometer. From the curves shown in Fig.2.13it can be seen that for moist soil the mutual inductance is reduced to a relatively small amount at separations of some hundreds to thousands of meters, this takes place for bedrock only for separations of some thousands to ten thousands of meters. From the Fig. it can be seen that the value of m decreases to an insignificant figure as the distance between

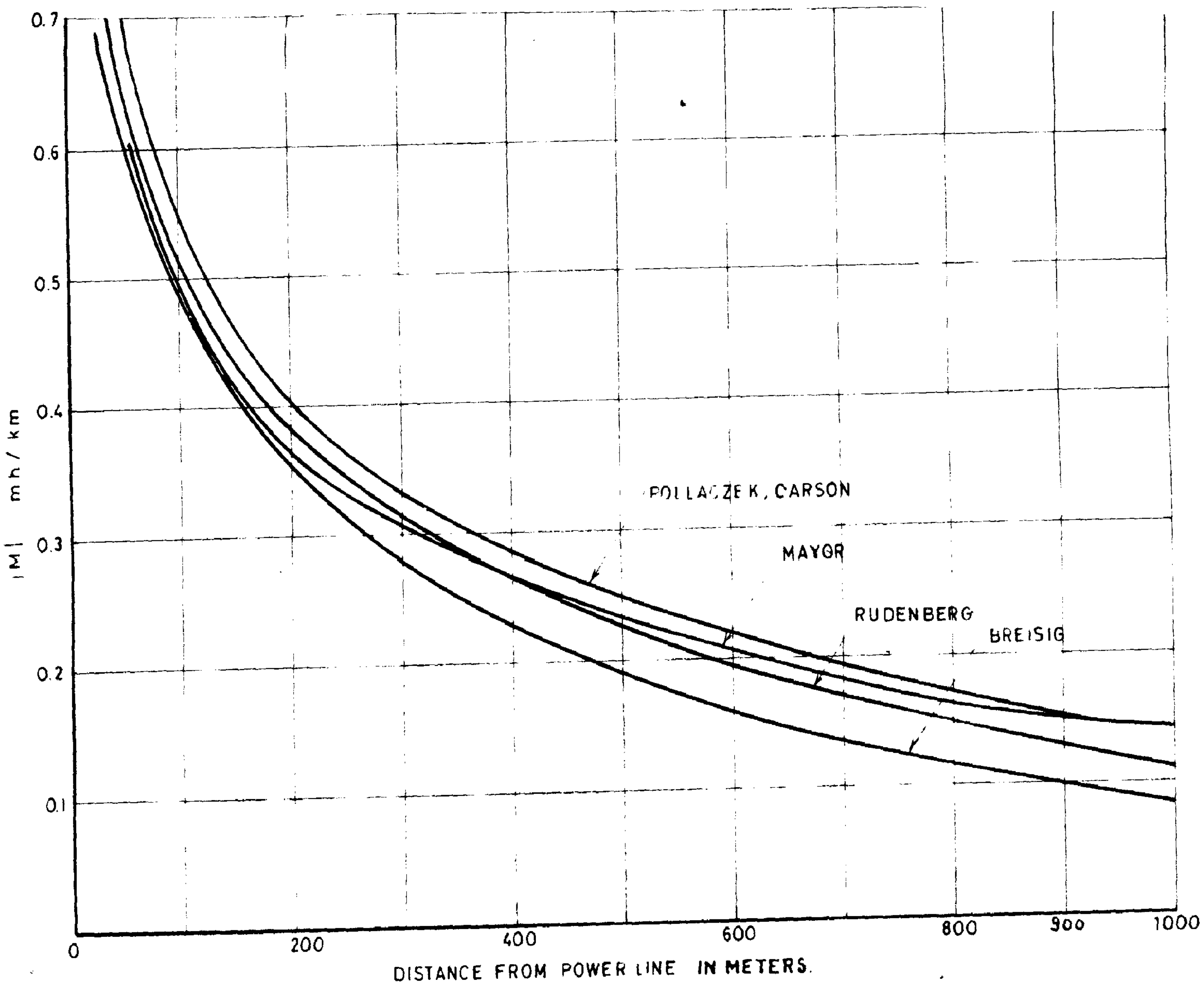


FIG.2-11 VARIATION OF MUTUAL INDUCTANCE WITH SEPERATION (f = 50c/s)

the two lines increases beyond 800 meters.

This problem of mutual interference with communication line has also been studied by Bresig, Mayor and Pollazck in Europe, and by Carson in America. As it is not possible to give details of the work of these investigators, the values of the mutual induction between the power and communication line obtained by the above investigators have been compared. Fig. 2.14 shows the variation of mutual induction with separation from power line, on the assumption that both induced and inducing lines are 6 m above the surface. The curves have been calculated according to five different methods. For those marked ''Pollaczek'' ''Rudenberg'' and ''Bresig'' a uniform earth resistivity equal to 200 ohms.m. was assumed and in the case of Mayor conducting layer 400 m. deep of resistivity 200 ohm meters. The basic assumptions assumed in the analysis by the authors have already been described in 2.2.3. From these curves it can be seen that the results due to 'Carson' and 'Pollaczek'' are identical. The curves of the Fig. 2.14 are in close agreement for smaller values of separation. At 1000 meters they have maximum difference of 50 per cent.
In 1925 the Comite Consultatif International directed that Rudenberg's formula should be used for the calculation of mutual inductance in the case of a parallel, between a power circuit having an earth connection and a communication circuit.

2.5.3 Magnitude of the Voltage Induced In the Communication L

If at a distance of 100 meters, a communication line runs parallel to the transmission line with current of I amps returning through the earth of resistivity $\rho = 100$ ohm.m., then using Rudenberg's formula the mutual inductance from fig. $m = 0.44$ mh./km.

Therefore the voltage induced in the communication line, from equation

$$
\begin{aligned}
e &= wm \times I \\
&= 314 \times 0.44 \times I \times 10^{-3} \\
&= 0.138I
\end{aligned}
$$

For a ground current of 10 amps.

$$e = 1.38 \text{ Volts. per kilometer.}$$

Obviously this voltage is insignificant.

According to C.C.I.T.T. regulations under normal conditions this induced voltage should not exceed 60 volts. Considering the above specific case, if the voltage is to be within 60 volts. the current limit is 43.5 amps which is far large from the considerations of safety in the power line itself.

Taking the load current passing through the ground as 10 amps, we can calculate the minimum distance of separation to be provided between these two lines so that the voltage induced in the communication line will not exceed 60 volts.

Length of Parallel in kilometers	Minimum distance of separation in meters.
20	10
30	40
40	92
60	200
100	500

This problem of mutual interference can be well studied by conducting the model tests on the scale model of the two lines in the electrolytic tank. This method will be discussed in Chapter 3.

CHAPTER 3

EXPERIMENTAL INVESTIGATIONS.

EXPERIMENTAL INVESTIGATIONS

3.1 MODEL TESTS:

The object of the model tests has been to represent the earth return path of a single phase earth return system of approximately 240 meters length. The problems studied were -

(1) Voltage gradient patterns along the earth return path due to different configuration of earth electrodes.

(2) Voltage induced in the neighbouring communication line, represented by a scale model and to study the effect of distance of seperation between these two lines on degree of interference.

3.1.2 Outline of the Scheme:

A model test method involves the following factors :-

(i) A large container called electrolytic tank open at the top and filled with proper electrolyte.

(ii) Scale model of the configuration of grounding arrangements.

Scale model of the neighbouring line

Current and voltage sources of appropriate magnitude.

Measuring voltages and currents.

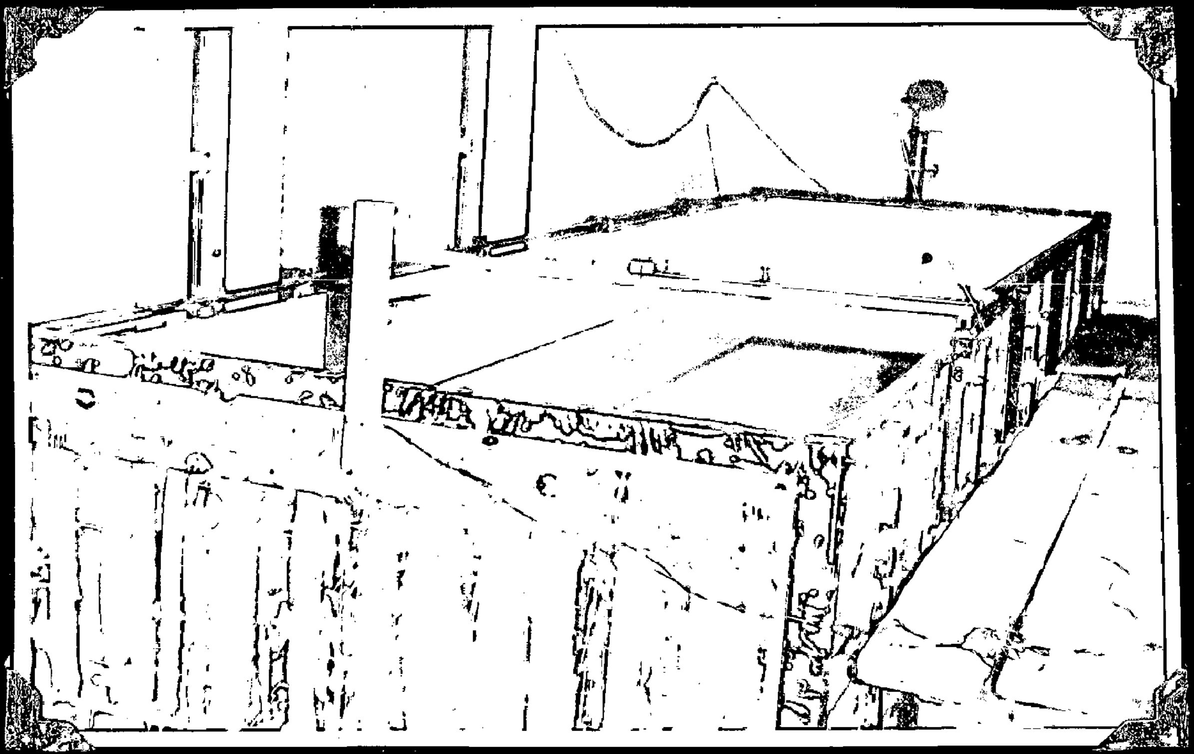
3.1.3 The Electrolytic Tank:

The wooden electrolytic tank has been built for conducting the model tests.(18) Taking the ratio of model to actual as 1 : 40 to represent earth return path of 240 meters, it is necessary to have length of the tank 6.00 meters. This length of the tank is also necessary so as to keep the model electrode and remote current electrode at a sufficient distance so that the field of the Model electrode is not affected by the presence of the remote electrode. The electrolytic tank is rectangular having inside dimensions 6.13x1.8x1.14 meters. The construction of the tank can be best appreciated from fig. 3.1. It has been made from 4 cm thick. Kelwood with proper joints which have been sealed with white-lead to make them, water-tight. This wooden tank has been enclosed in a steel frame which serves to maintain requisite pressure and resist the bulging of wooden walls due to lateral thrust of the electrolyte in the tank. The inside of the tank was first imprignated with linseed oil and then thoroughly painted with white-lead paint so as to stop the water leakage.

3.1.4 Mode of Studies in the Electrolytic Tank:

3.1.4.1 Earth :

When the earth is assumed to be of uniform resistivity it can be represented by a suitable electrolyte in the tank. The tap water has been used to represent homogenous medium of earth. The conductivity of the electrolyte can be varied by addition of the salt.



THE WOODEN ELECTROLYTIC TANK

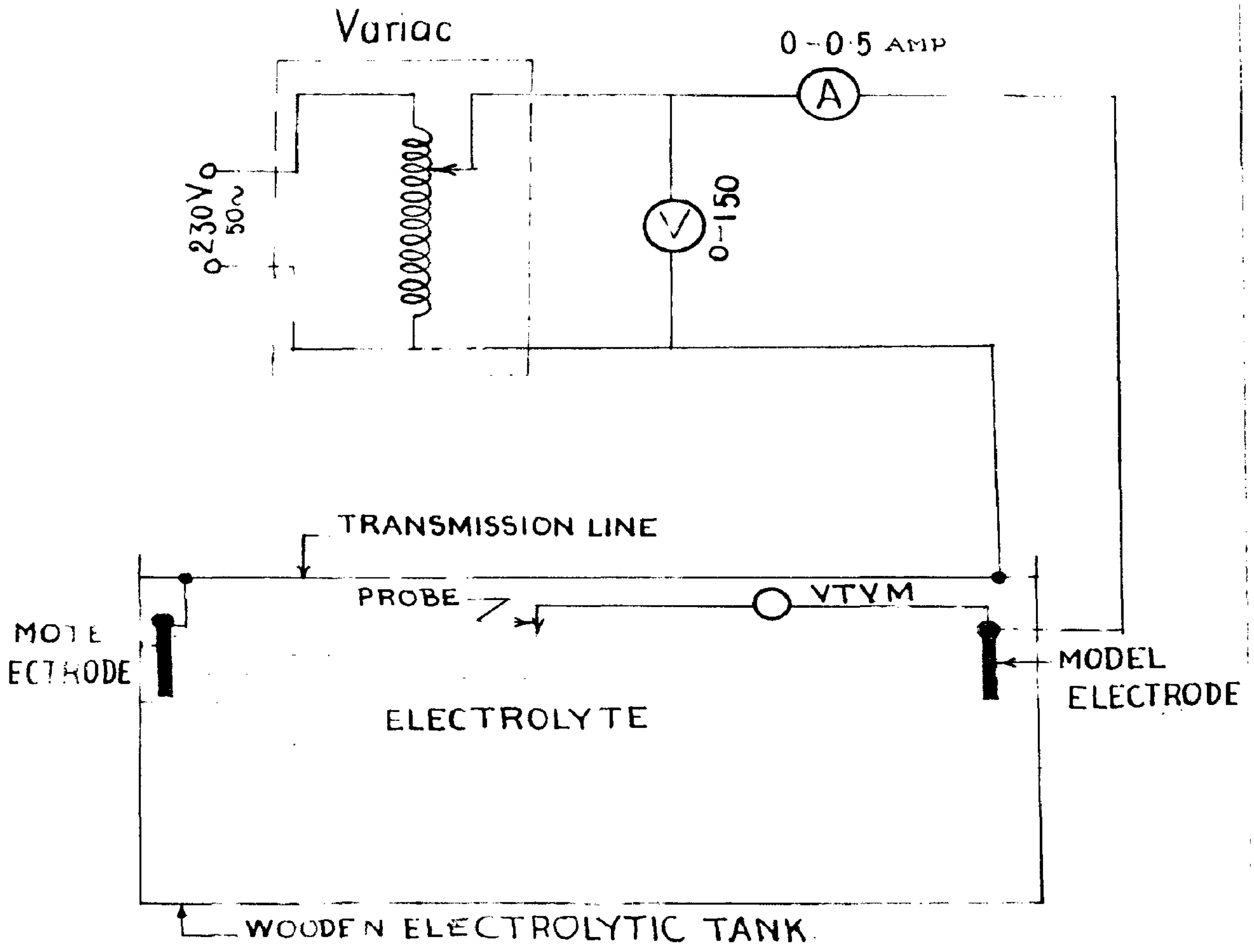
Generally, the earth is not homogenous and consists of multiple layers of widely different resistivity. The influence of uniform earth resistivity on the voltage gradients can be studied in the two layer electrolytic tank with controllable layer depth and resistivity. Mixture of sand clay and graphite powder placed at the bottom of the tank can be used to represent the lowest layer of the non-homogenous earth and upper layer can be represented by tap-water. However, the studies were conducted assuming the earth as homogenous and having uniform earth resistivity.

3.1.4.2 Earth Electrodes:

The resistance of hemisphere imbeded at the surface of uniform soil is $R = \frac{P}{2\pi r.}$ discussed in 2:3:1 and for a driven ground rod a good approximation is

$$R = \frac{P}{2L\pi} \text{Log}_e \left(\frac{4L}{a} \right) \quad \ldots \ldots (3.1)$$

As the resistance is proportional to earth resistivity and inversely to the length, it is possible to use scale models of electrodes in the electrolytic tank to simulate actual electrodes.(19) It is evident from the above equations for electrode resistance that the resistance is determined primarily by the largest dimension, i.e. length of the electrode. Hence in model tests lengths should be accurately to scale but the exact diameter of the model electrode is not too important. Adopting model to actual ratio as 1 : 40 a rod electrode 4 meters in length and 2 cm. in diameter should be represented by a model of 10 cms in length and $\frac{1}{20}$ cm in



EXPERIMEINTAL SET-UP

Fig 32.

diameter. But it is difficult to construct rigid models with such smaller diameter wires. Hence a higher diameter wire, 16 gauge, has been employed making the model structure more rigid. The model electrodes were attached to the piece of insulating material and their depth of immersion was varied manually.

3.1.4.3 Representation of the neighbouring Line:

The earth return path of the neighbouring communication line has been represented by two electrodes spaced at a distance equal to the length of the communication line and parallel to the power line at required distance of separation. The distance of separation between these two lines can also be varied at will.

3.1.4.4 Experimental Set-up :

Schematic diagram for the experimental set-up is shown in fig 3.2 . Low voltage variable supply is given to the system.The probe, an exploring electrode, has been used to simulate the surface contact with electrolyte for measuring surface gradients.An insulated wire, with the insulation cut back about 0.25 cm. has been used as the probe. The probe was mounted on a movable carriage as shown in fig. 3.1 which enables the point of the probe to be moved on the surface of the electrolyte.The current in the model electrode was kept below 0.2 amp so as to keep down polarization at the electrode.The surface potentials have been measured with vaccum tube voltmeter.

SURFACE POTENTIAL DISTRIBUTION ALONG THE ROUTE OF THE TRANSMISSION LINE

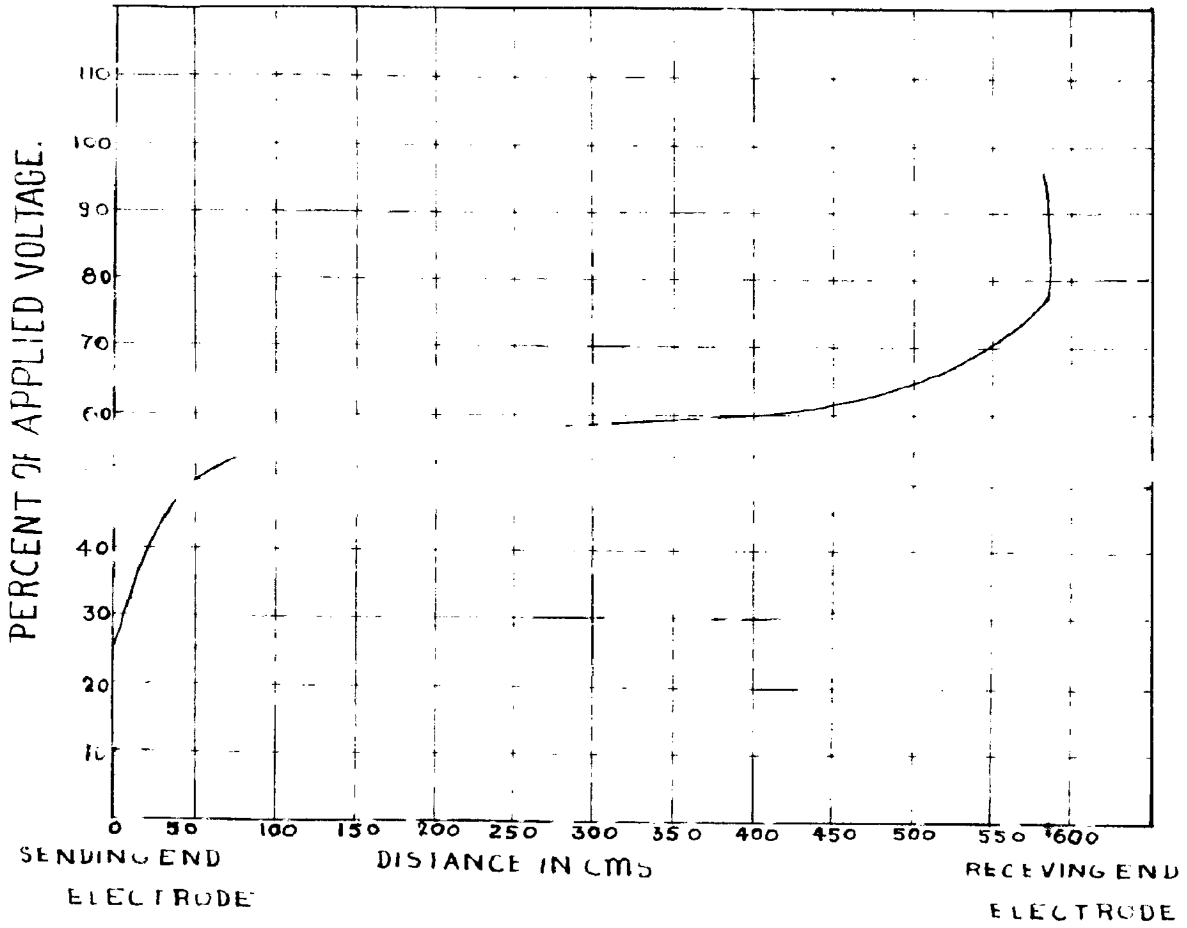


Fig 3.3

3.14 EXPERIMENTAL RESULTS:

The surface potential distribution for the single driven rod, multiple rods in different configuration, plate electrodes and buried horizontal wires was studied. Surface potentials were measured along the dotted line towards the remote electrode. The results obtained are shown in the Fig. 3.3. to 3.13. In all the surface potential curves, distances from the reference point towards remote electrode are plotted on x axis and the surface potential on y axis. The model ground current was kept at 0.1 ampere throughout the experiment.

The resistivity of the electrolyte i.e. tap water with added salt was measured by the conductivity meter. The resistivity of the electrolyte during that particular experiment is indicated in the respective figures.

3.16. DISCUSSION OF THE RESULTS

3.16.1 Surface potential distribution along the route of the Line:

Fig. 3.3 gives the surface potential distribution for driven rod of 5 cm used as the earth electrode at both ends. It can be seen from the figure that the surface potential increases as we go away from the sending end electrode. This increa in surface potential is appreciably high in the vicinity of the electrode . After some distance the surface potential becomes nearly constant. As we approach the remote electrode the surface potential again increases and attains the maximum value at the remote electrode.

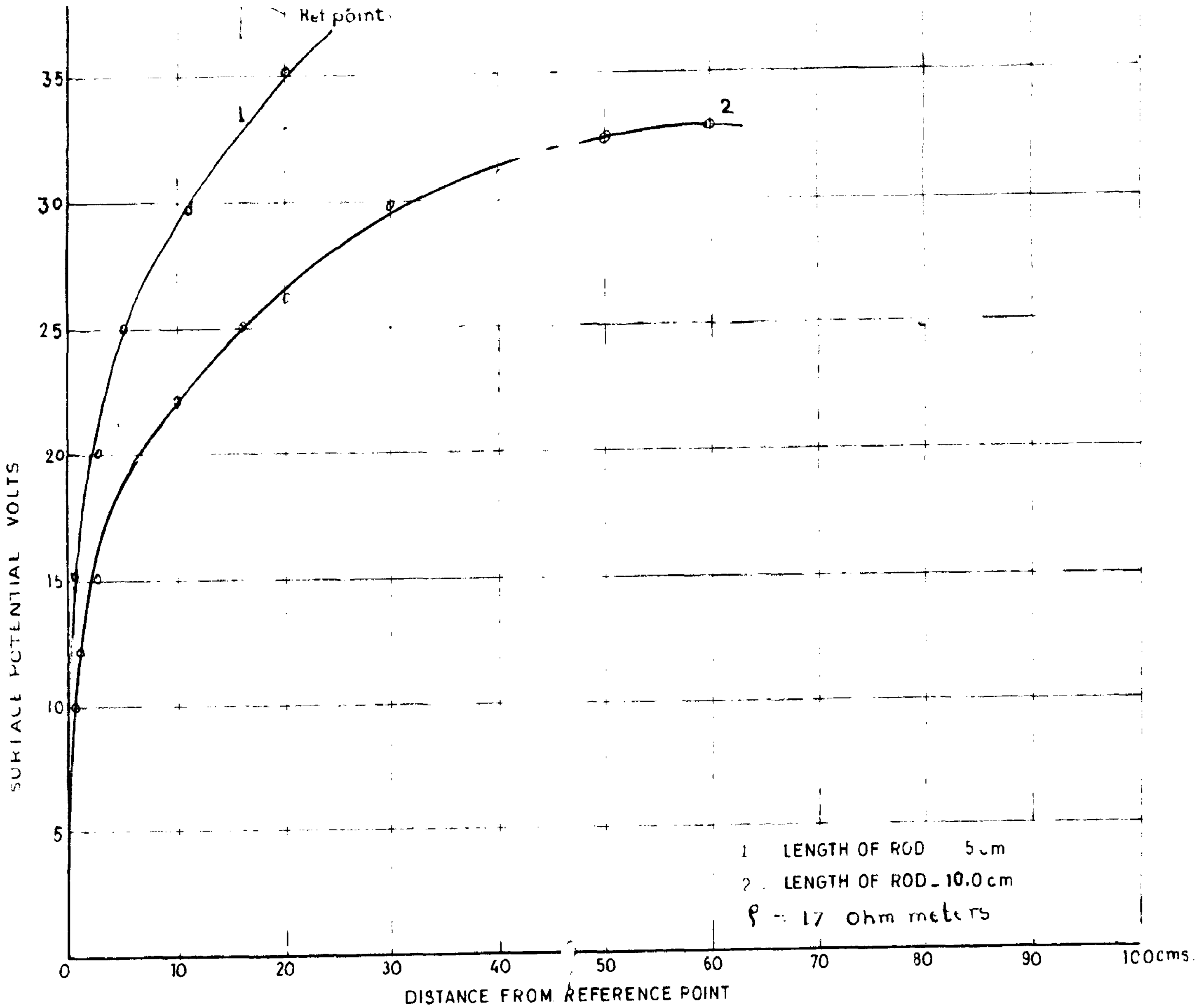


FIG.34 SURFACE POTENTIAL DISTRIBUTION FOR DRIVEN ROD

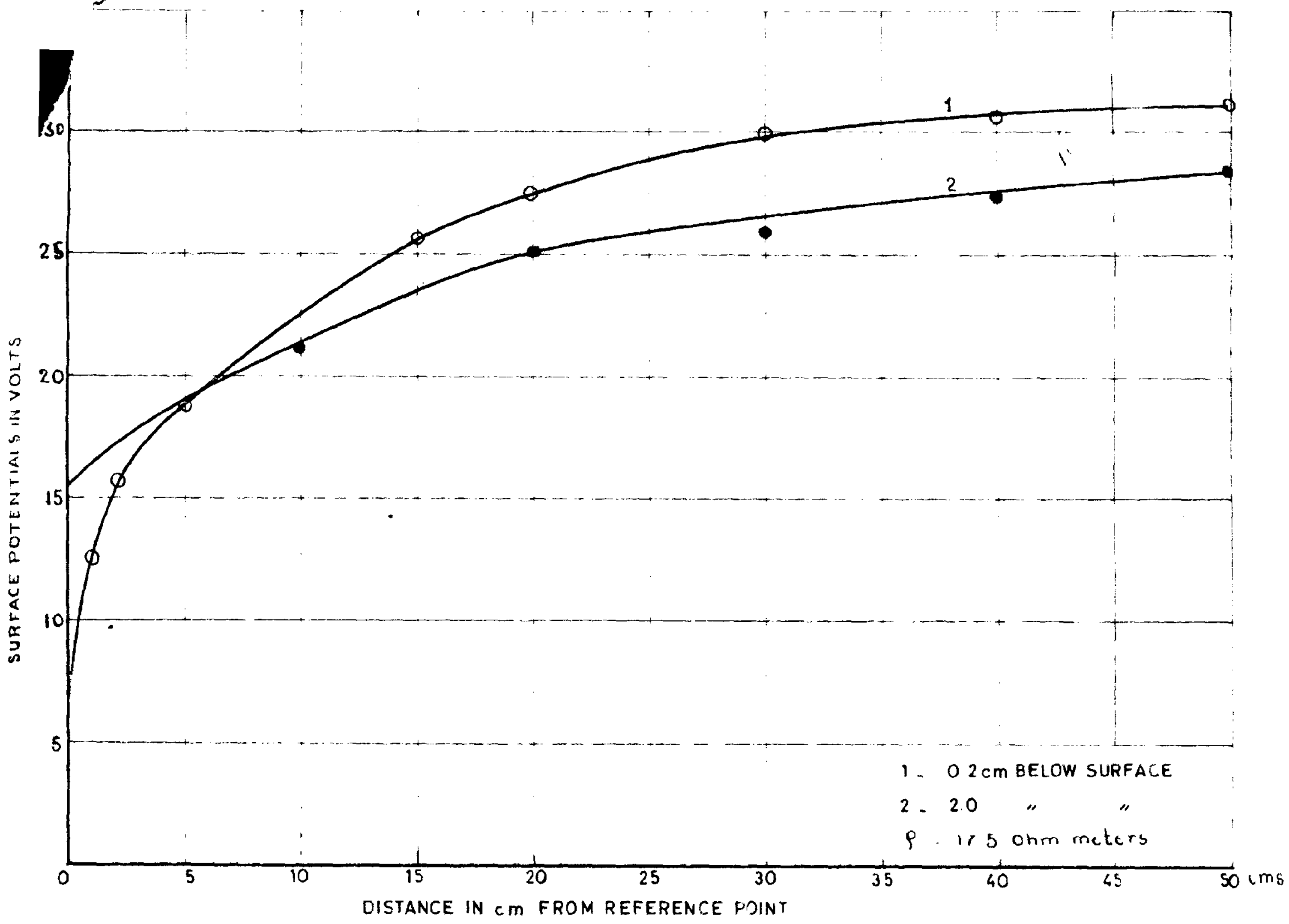


FIG.3.5 EFFECT OF DEPTH OF BURIAL FOR SINGLE DRIVEN ROD OF 15 cm LENGTH

3.1.5.2 DISTRIBUTION OF SURFACE POTENTIAL NEAR EARTH ELECTRODE DRIVEN ROD :

Effect of length of Rod-

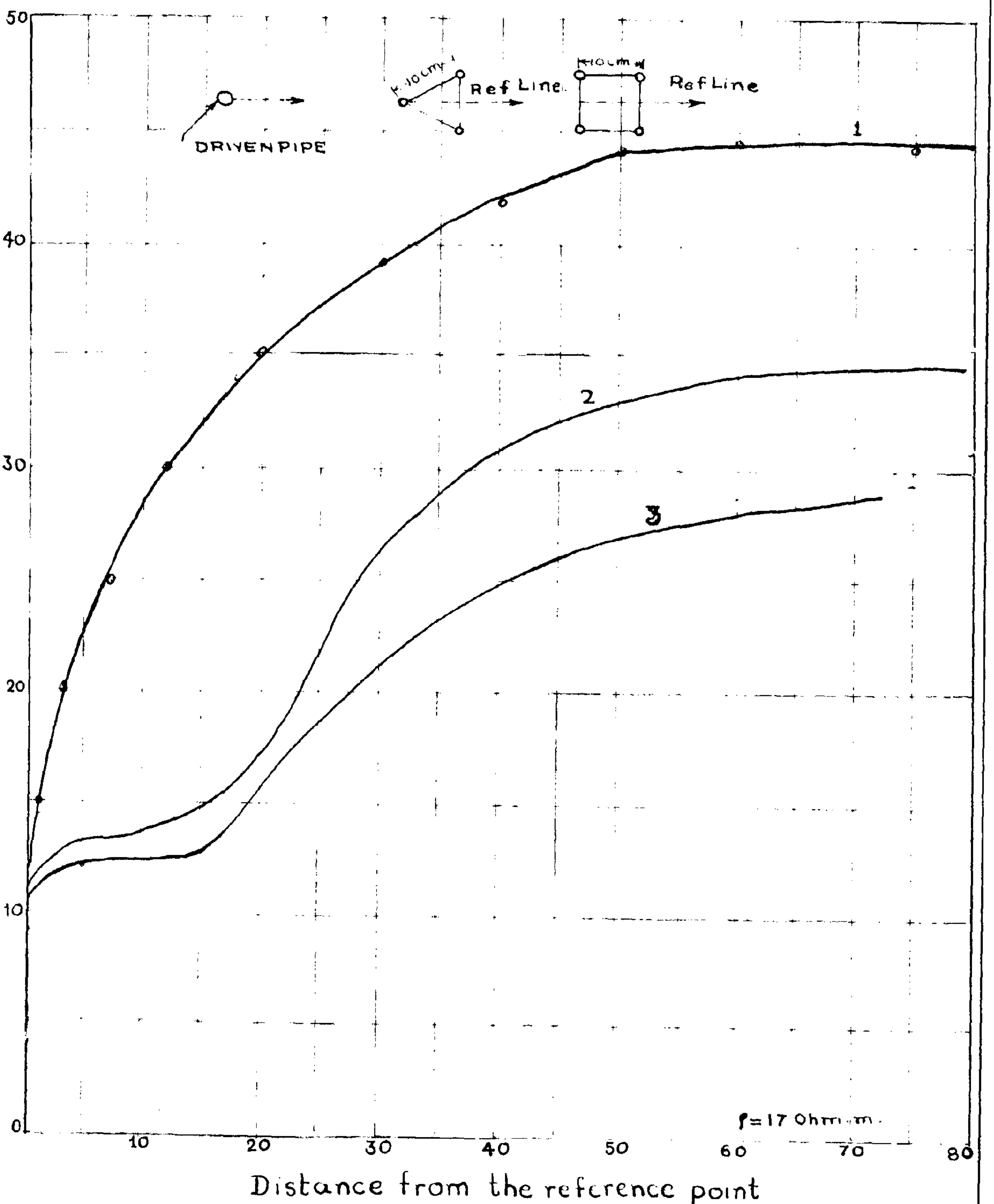
In fig. 3.4 curve 1 gives the surface potential distribution for a driven rod of length 5 cms(2 meters in actual) and curve 2 gives the potential distribution for a driven rod of length 10 cms.(4 meters). It is evident from the curves that the use of 10 cms (4 meter) rod electrode has only negligible effect in reducing the potential gradient. It can be observed from the curves that very high surface potential exists in the vicinity of the single driven rod. Hence the shock hazard due to touch potential is greatest with single driven rod and hence the use of single driven rod should be avoided.

Effect of depth of burial-

Fig. 3.5 shows the effect of depth of burial of electrode on potential gradients. Curve 1 gives the potential distribution for a single driven rod buried to a depth of 0.5 cm(.2 meters below the earth's surface and curve 2 shows the potential distribution for the rod buried to depth of 2 cm.(.8 meters) below the earth's surface. It can be seen that deeper burial reduces the step voltages further but increases the touch potential.

Effect of Configuration -

Fig. 3.6 illustrates the potential distribution for the different configurations .Curve 2 gives the potential for three rods placed at the nodes of equilateral triangle of 10 cm sides



EFFECT OF CONFIGURATION.

Fig 3.6

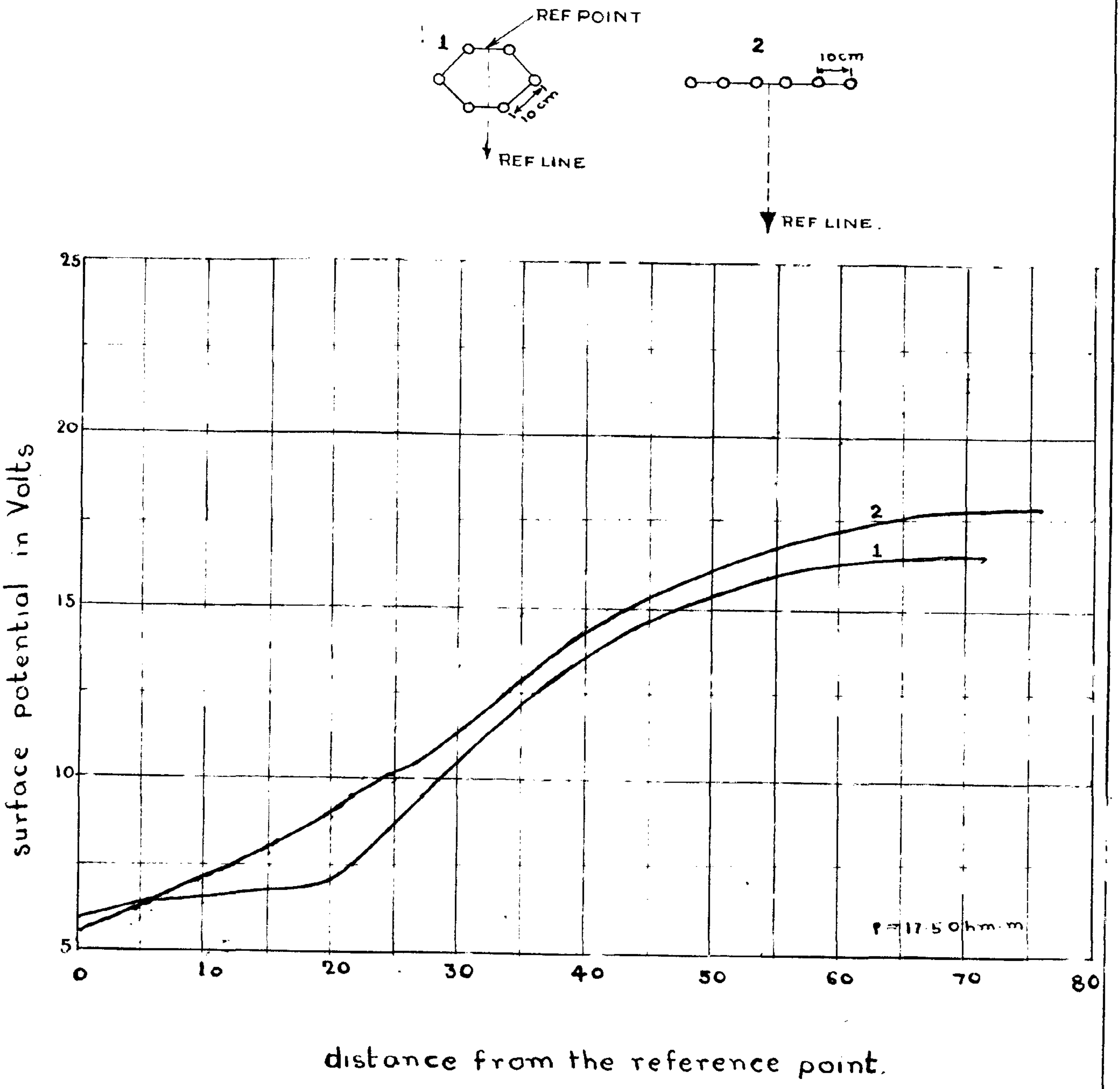

REF POINT
1
10 cm
REF LINE
2
10cm
REF LINE.
25
20
15
10
5
surface potential in Volts
0
10
20
30
40
50
60
70
80
2
1
ρ = 17.5 Ohm·m
distance from the reference point.

Fig 3.7.

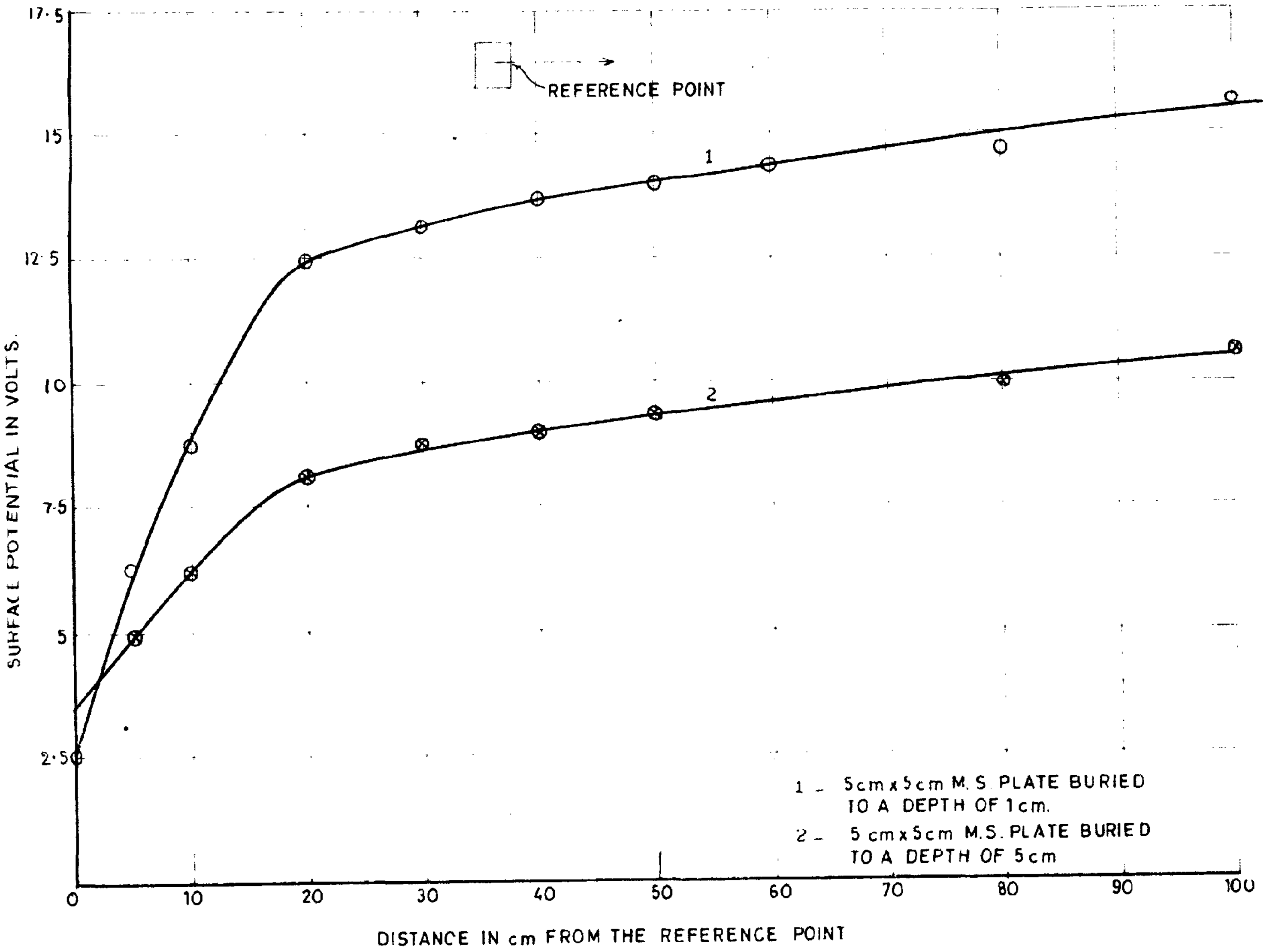


FIG.3.8. SURFACE POTENTIAL DISTRIBUTION FOR PLATE ELECTRODES

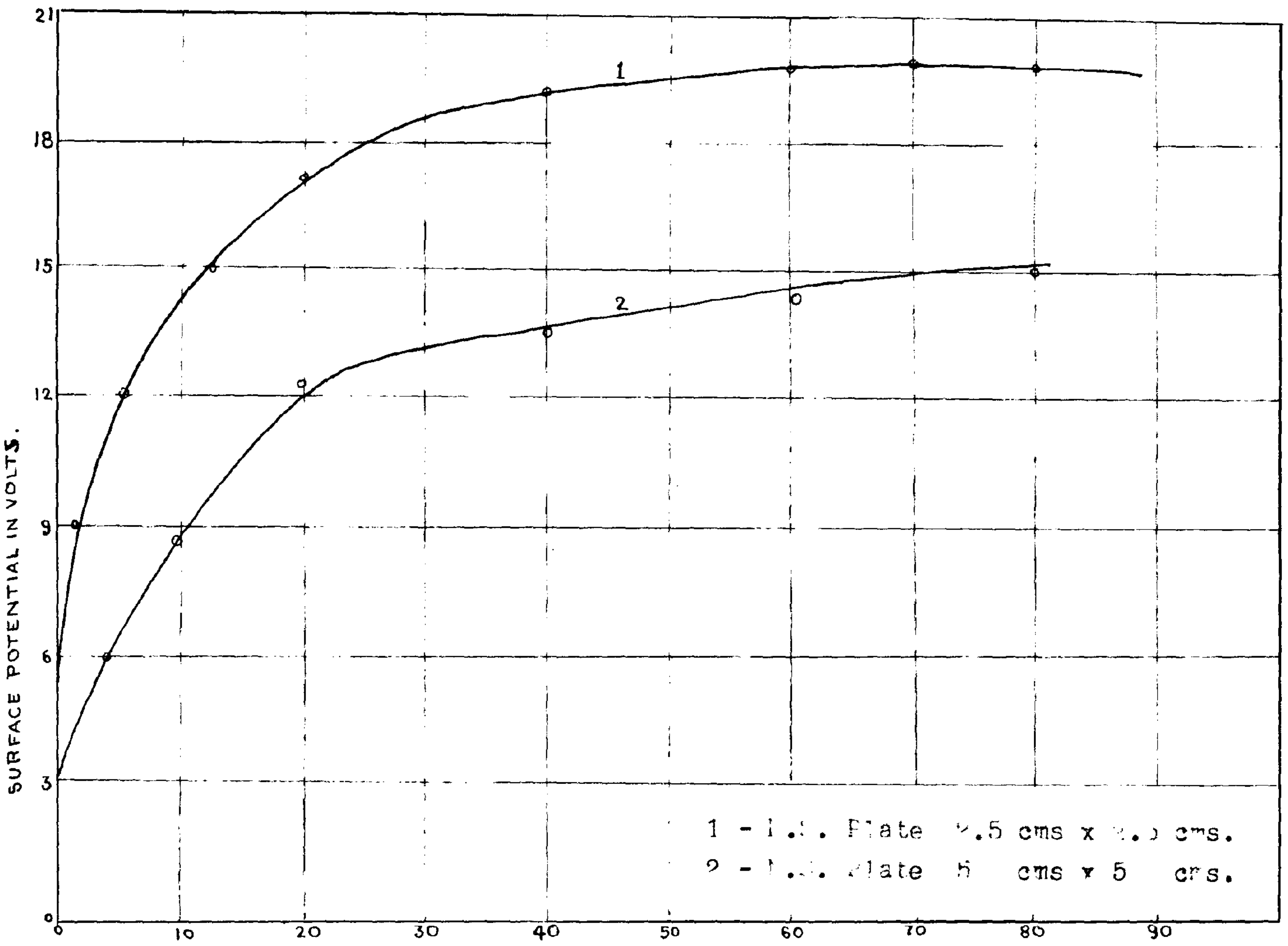


Figure [illegible]

SURFACE POTENTIAL DISTRIBUTION FOR PLATE ELECTRODE

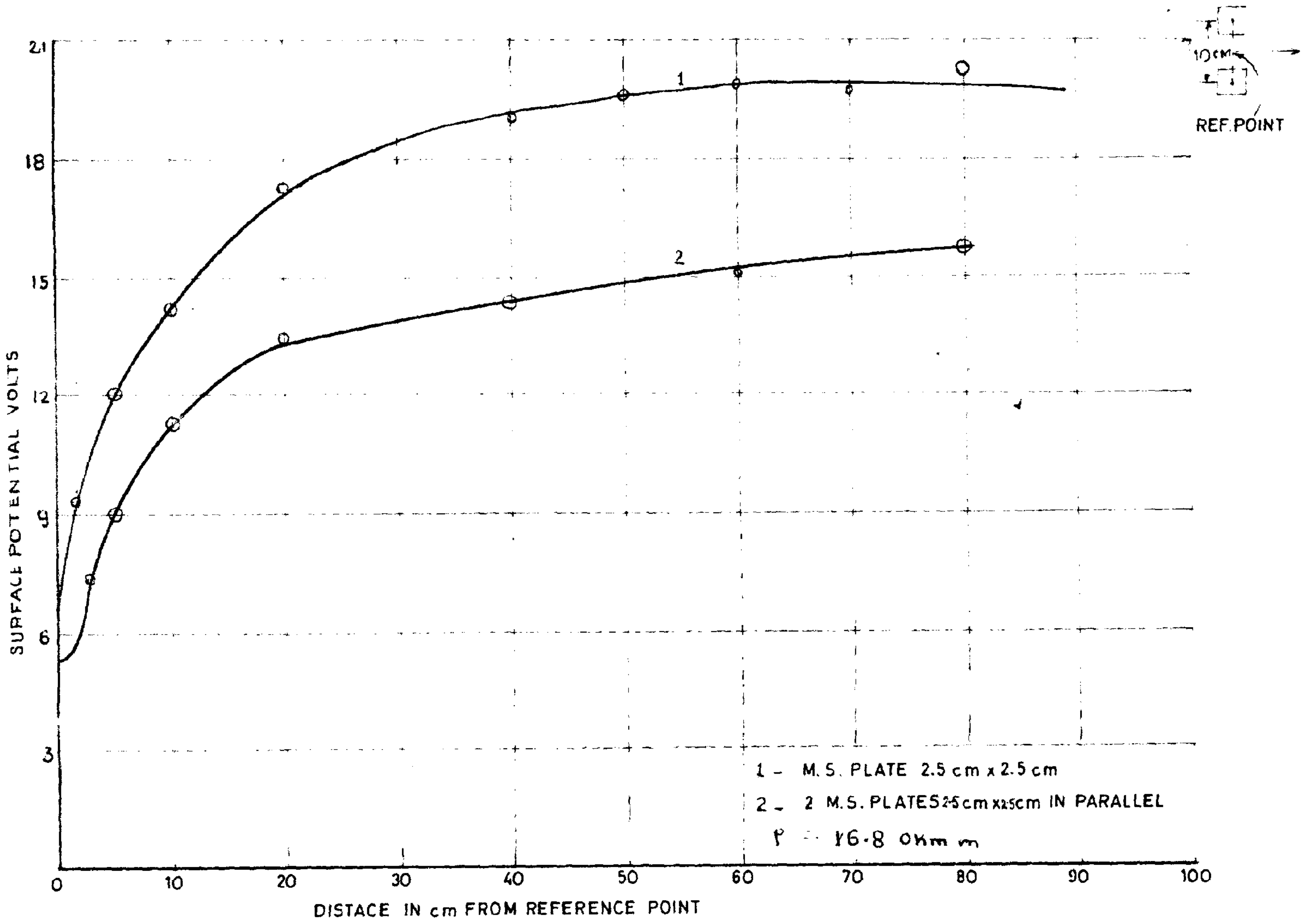


FIG.3·10 SURFACE POTENTIAL DISTRIBUTION FOR PLATE ELECTRODE

SURFACE POTENTIAL DISTRIBUTION FOR BURIED HORIZONTAL WIRE

EFFECT OF LENGTH OF BURIED WIRE

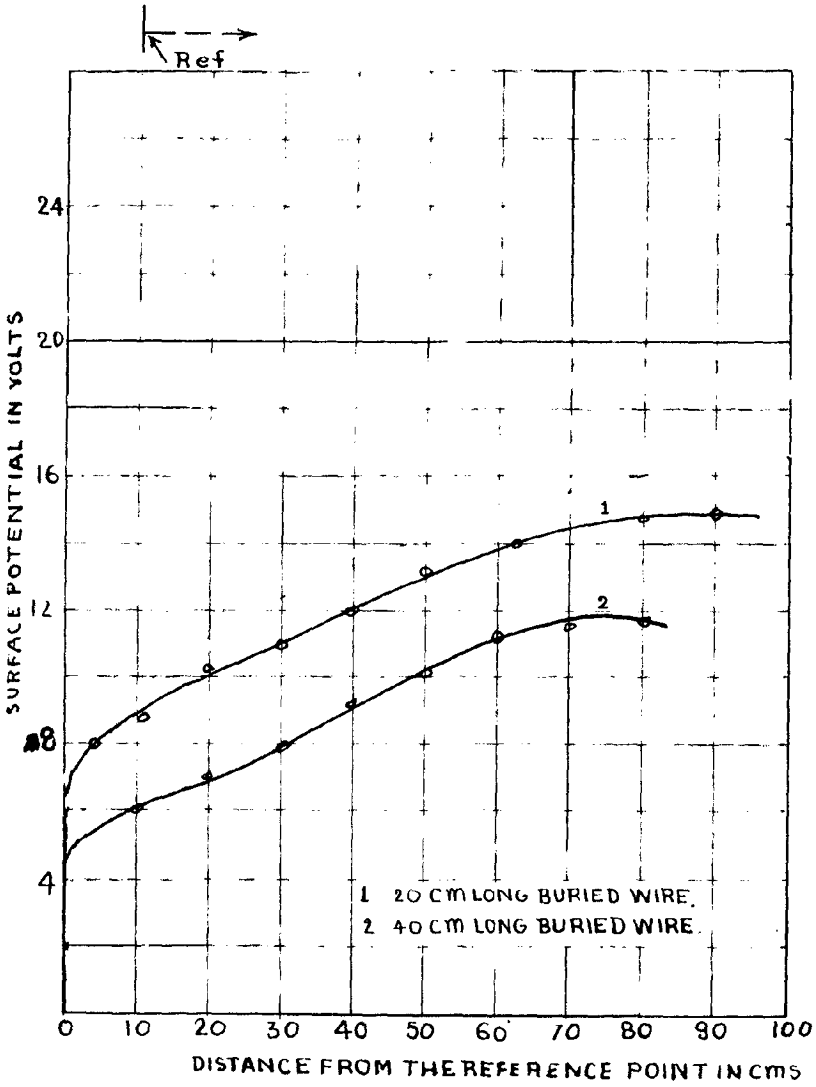


Fig 3.11

and curve 3 shows the potential distribution for four rods in square of 10 cm sides and connected in parallel.

It is evident from the above curves that by employing either a triangular or square configuration potential gradients can be reduced to considerable extent.

In fig. 3.7 curve 1 gives potential distribution for 6 rods arranged in regular hexagon of 10 cm sides and curve 2 gives the potential distribution for the same rods arranged in straight line with distance of separation of 10 cm between two rods.These curves show that there is slight decrease in the surface potential when the rods are arranged in straight line.

Plate Electrode :

Fig. 3.8 shows the distribution of surface potential for a M.S.Plate of size 5 cm x 5 cm (2m x 2 m) . It can be observed from the graph that the nature of potential distribution is similar to that for driven rods.From the curves in the figure 3.8 it is seen that increasing the depth to which the plate is buried decreases the surface potentials.Fig. 3.9 shows the effect of the area of the plant on potential distribution.The increase in area of plate decreases the surface potentials.

The curves in fig.3.10 show thatw using two plates in parallel results in reduction of the surface potential.

Horizontal buried wires :

Fig. 3.11 shows the surface potential distribution for

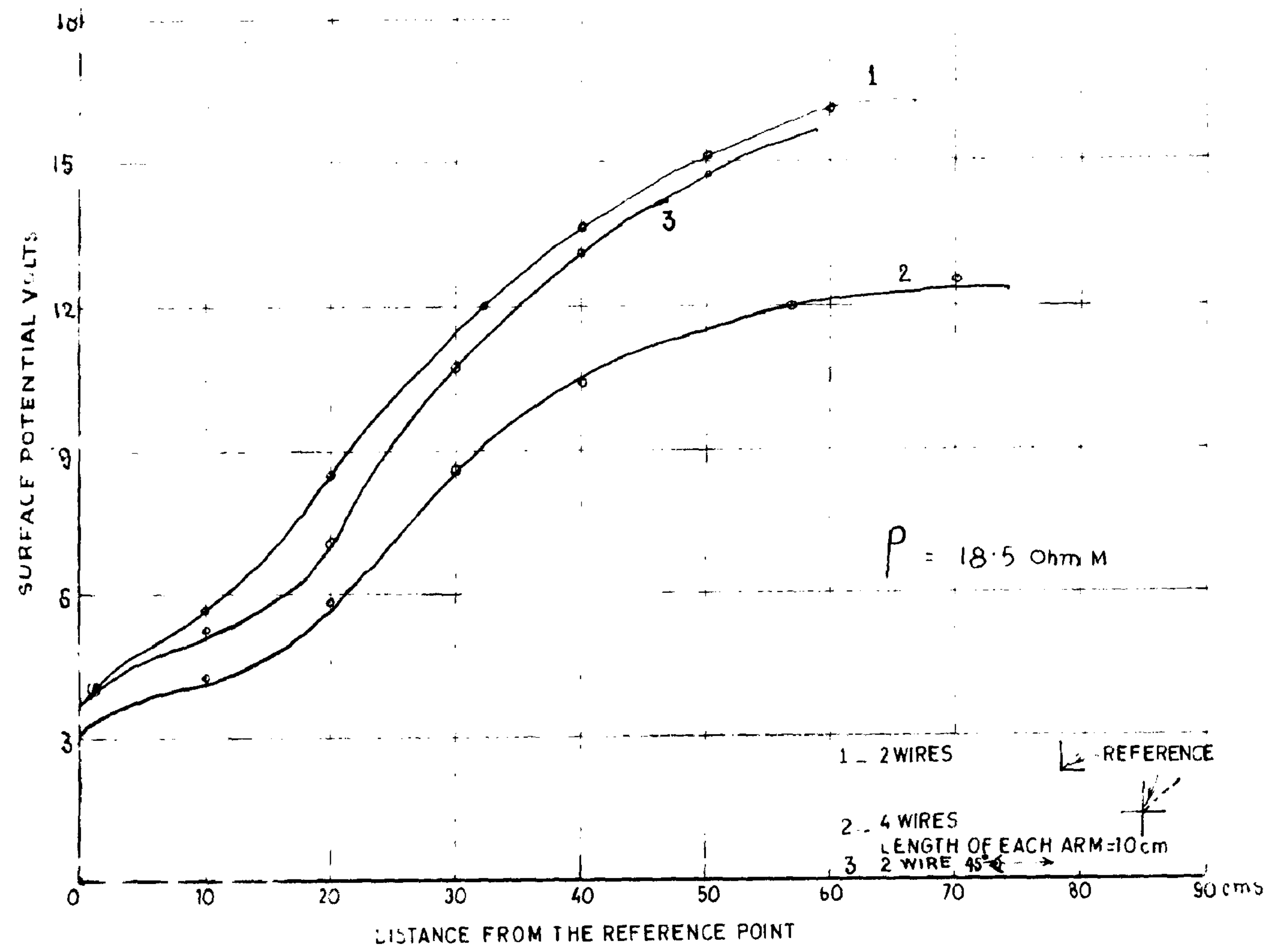
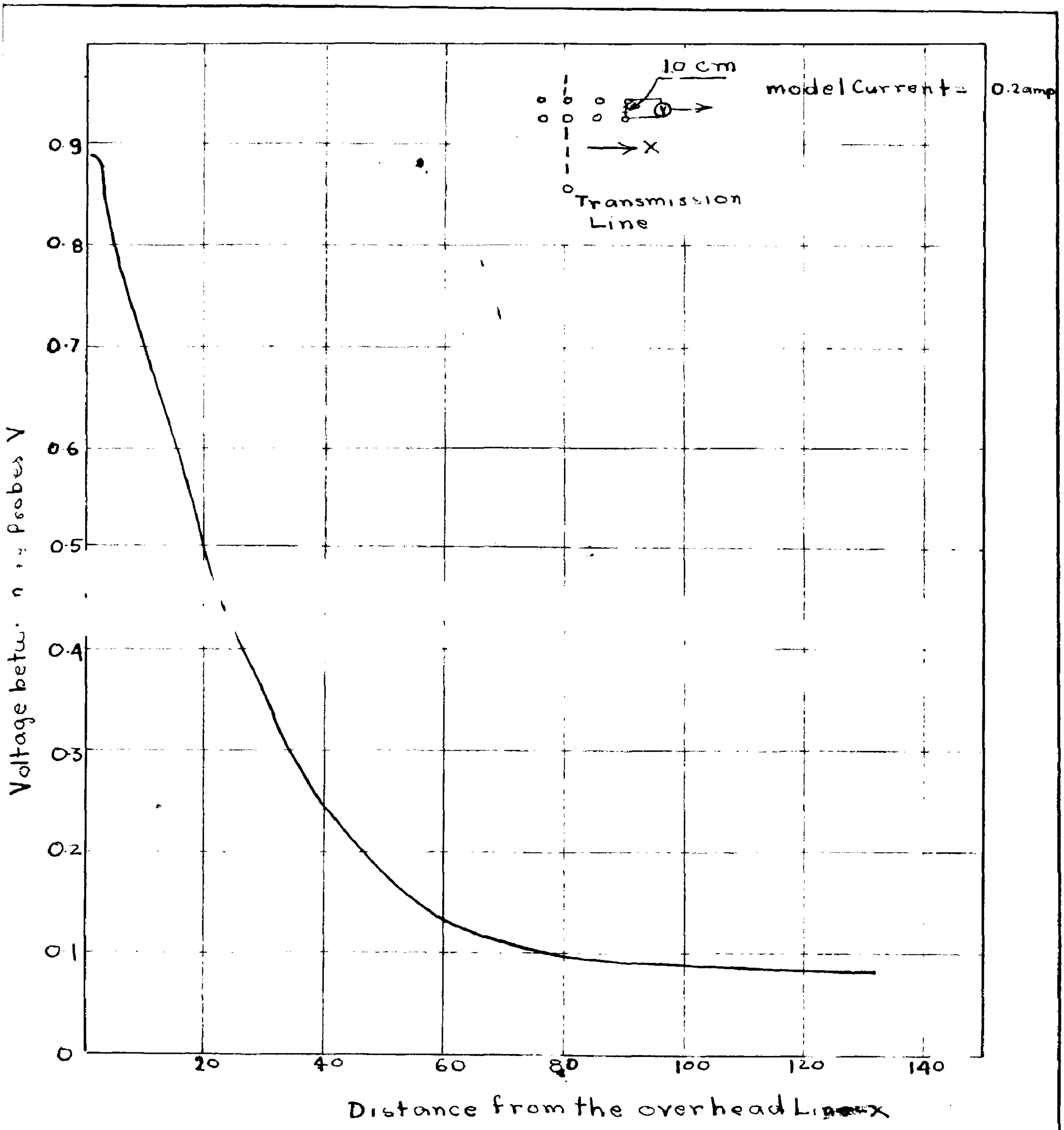


FIG.3.13 SURFACE POTENTIAL DISTRIBUTION FOR HORIZONTAL BURIED WIRE



BEHAVIOUR OF CURRENT FLOWING IN THE EARTH.

Fig 3.14

horizontal buried wires of length 20 cm and 40 cms buried to a depth of 1 cm. It is evident from the figure that the length of the buried wire decreases the surface potentials.

In Fig. 3.13 curves 1 to 3 give the surface potential distribution for two 20 cms. long buried wires at right angle and four buried wires 10 cm long in the four point star. From these curves it is evident using 4 radial wires decreases the touch potential as well as the step potential. Curve 2 gives the surface potential distribution for two wires of 25 cm length placed at an angle of 45°. It is observed that for this 45° configuration the potentials are slightly reduced as compared to 90° configuration.

3.16. Current distribution in the earth return path

Fig. 3.14 gives the voltages between two electrodes placed 20 cm apart and at various distances from the transmission line but at considerable distance from the ground electrodes provided for carrying current of the power line to the earth. The voltage between these two points or electrodes is directly proportional to the resistance between them and the current flowing there. As the electrolyte is having uniform resistivity one can say that this voltage drop is proportional to the current flowing through the earth at the point. Hence from these measurements it can be said qualitatively that the current distribution in the earth return path will also be of the same nature as is given in the figure.

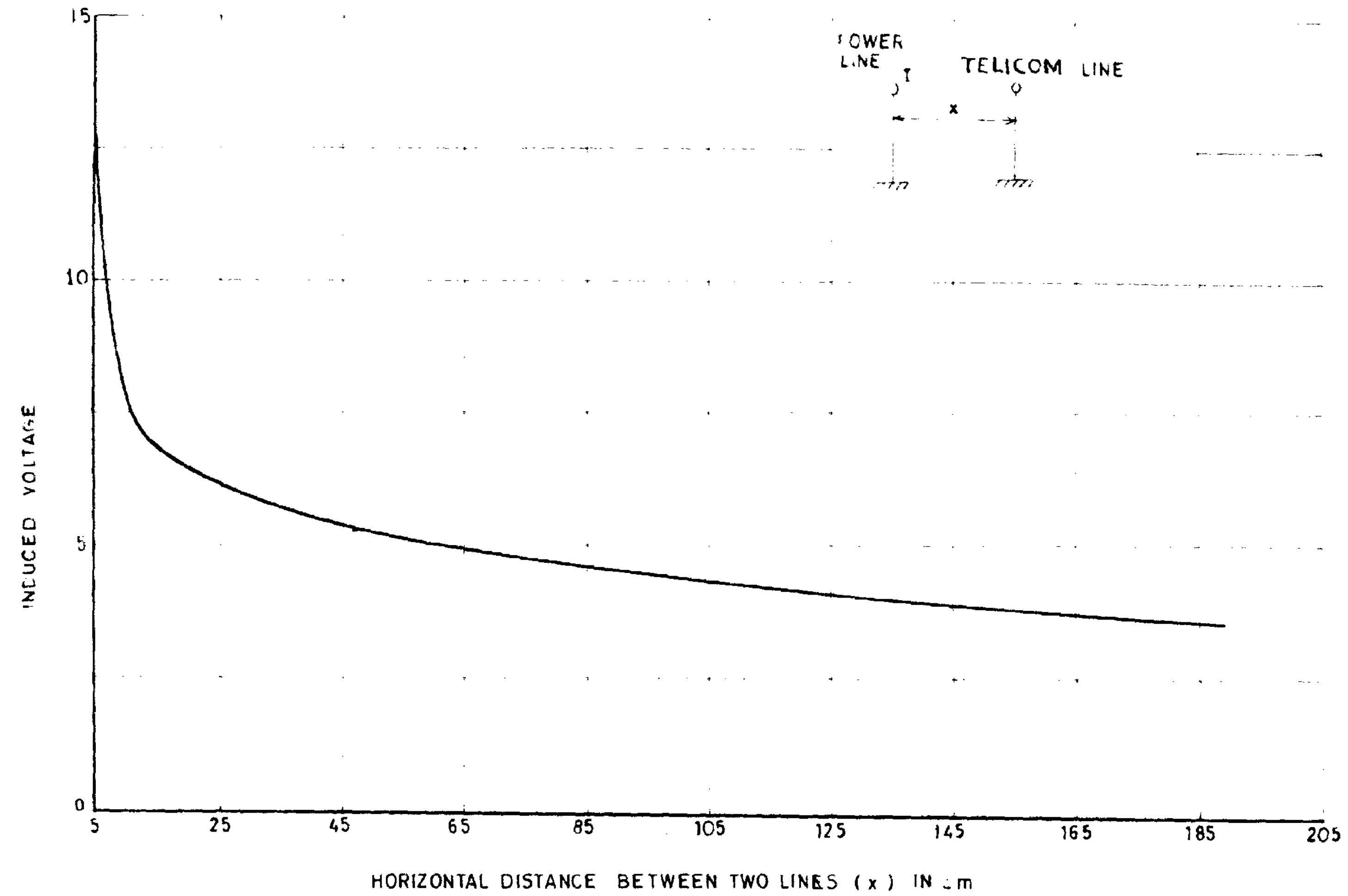


FIG.3.15 MUTUAL INTERFERENCE WITH COMMUNICATION LINE

3.1.7 Interference with the communication line:

Fig. 3.15 gives voltage induced in the communication line of length 160 meter running parallel to power line at various distance of separation.The model current flowing in the power line was adjusted to 0. 1 amp. and the voltage induced in the model telecommunication line by vaccum tube voltmeter. From the fig. 3.15 it is evident that the voltage induced in the communication line depends largely on its distance of separation from the power line.The voltage induced in the communication conductor decreases with the increase of distance of separation in accordance with the curve. However, the induced voltages obtained in the model tests are higher than the theoritical values.This may be due to the effect of the field around the sending end and receiving end electrode of the power line.In theoritical treatment of the problem the effect of field around the electrodes conveying power current to the earth has been neglected.

3.1.8 Application of Test Results :

The relation between the resistance of the grounding system (model or prototype) the length of the conductor and the average resistivity of the homogenous media(electrolyte or soil) is as follows :

$$R_P \propto \frac{\rho_P}{L_P} \quad (20) \quad \ldots (3.2)$$

and

$$R_m \propto \frac{P_n}{I_M} \quad \ldots (3.3)$$

Where suffix P and M denote parameters for prototype and model respectively. Similarly the relation of the surface potentials for the model and prototype is given as :

$$E_P \propto \frac{\rho_P I_P}{L_P} \quad \text{- - - - - - (3.4)}$$

and

$$E_M \propto \frac{\rho_M I_M}{L_M} \quad \text{- - - - - - (3.5)}$$

Therefore

$$\frac{E_P}{E_M} = \frac{\rho_P}{\rho_M} \times \frac{L_M}{L_P} \times \frac{I_P}{I_M} \quad \text{- - - - (3.6)}$$

Where I_P and I_M denote currents for prototype and model respectively.

For the model to actual ratio adopted for model tests

$$\frac{E_P}{E_M} = \frac{\rho_P}{\rho_M} \times \frac{40}{1} \times \frac{I_P}{I_M} \quad \text{- - - - . (3.7)}$$

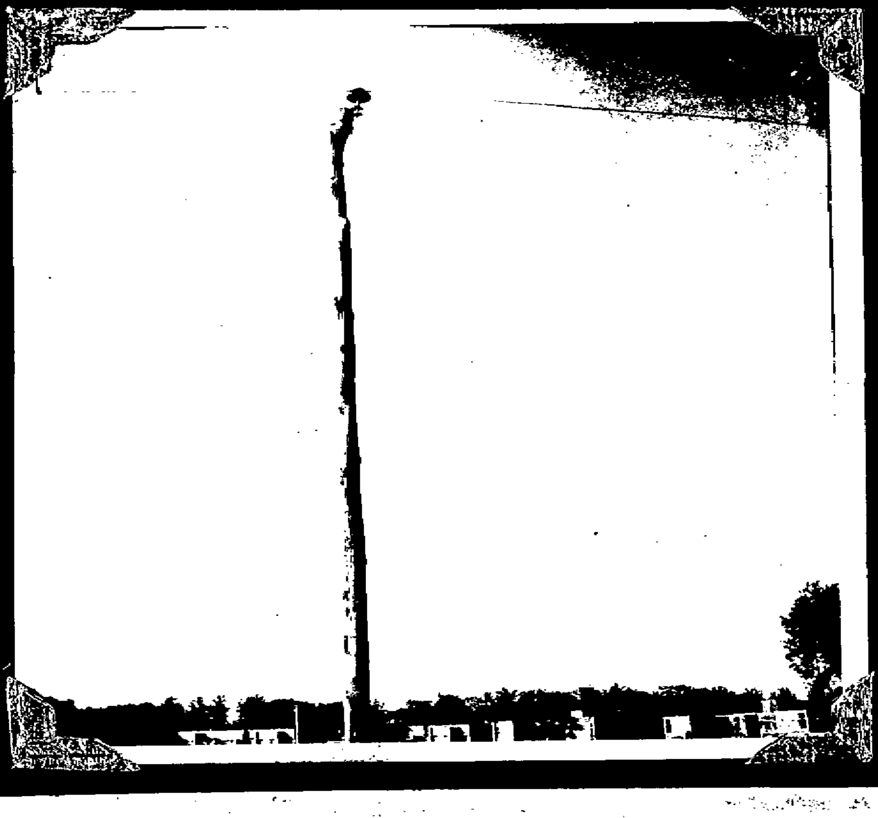
By the application of this formula the results obtained in the model tests will be compared with the result obtained in the field studies in the Chapter 3.2

3.2 FIELD TESTS:

3.2.1 The experimental single phase single wire line with transformers etc was erected in the University premises to study the problems involved in the use of this system.Before studying the actual performance of the line it is of prime importance to have thorough knowledge of the resistivity of the earth in that area and hence the survey of earth resitivity was undertaken for the area in which the experimental line has been installed. Different types of ground electrodes were installed in the area both at the receiving and sending ends of the line. The resistance to earth of these various electrodes were measured. The voltage gradients for these different electrodes were measured actually by passing current through them. The determination of the resistance and reactance of the earth return path is important from the point of view ofl loss and regulation in such system. Test has been carried out to determine the impedance of the earth return path of the single phase single wire line.

3.2.2 Experimental Single Phase Earth return line :

Length of the line	.. .. ..	240 meters
Conductor	.. .. ..	8 SWG G.I.WIRE
Transformers -		
Sending end	.. .. ..	230/1250 Volts .10 KVA Sacis.Single Phase Transformer.
Receiving end	.. .. ..	1250 Volts/230 Volts 10KVA Socis Single phase.



THE EXPERIMENTAL SINGLE WIRE LINE

Supports	.. ..	Wooden poles 24' high above the ground.
Span	.. ..	50 meters.

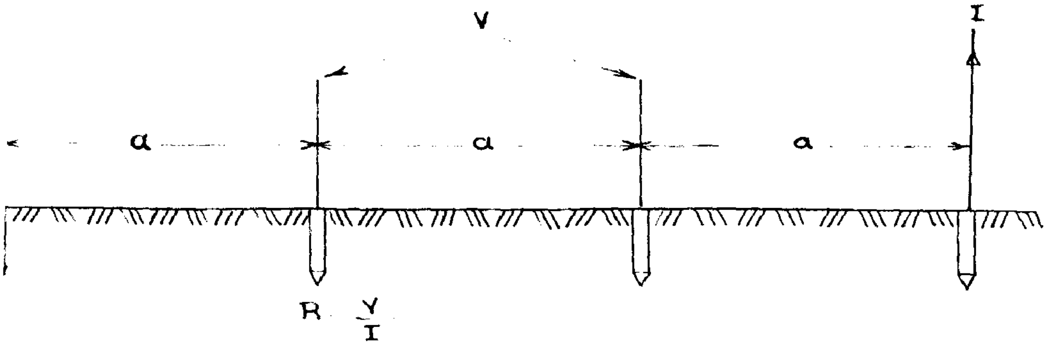
The single conductor was carried over the insulator which was mounted on the pole with the clamp as shown in fig 3.16

3.2.3 MEASUREMENT OF EARTH RESISTIVITY:

The specific resistance of the earth can be measured in the following manner. Four electrodes are driven in the ground at intervals a meters as shown in fig 3.17. A current I amperes is passed through the soil between the outer electrodes, and the potential difference V volts between the inner electrodes is measured the quotient V/I gives a resistance R. Then the specific resistance in ohm meters is given by the formula

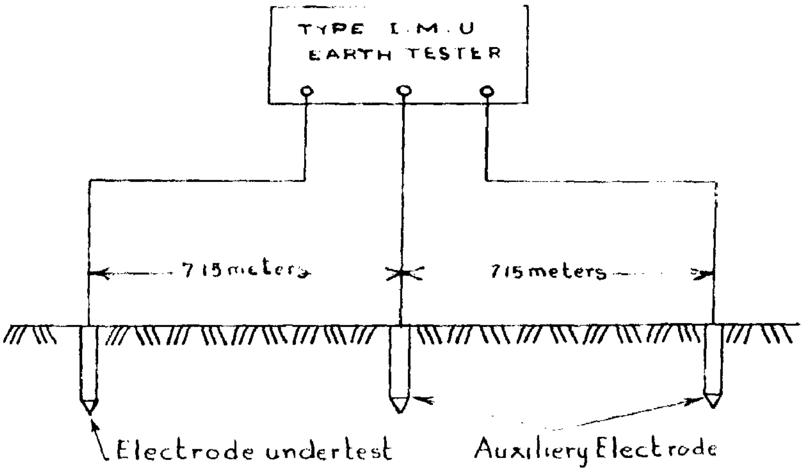
$$\rho = 2\pi aR \quad \text{ohm.m.}$$

The depth ~~of~~ the electrodes are driven in the ground must be small compared with a . Different types of earth testers, based on the above principle, are available. The earth tester type IMV was used to measure earth resistivity of the area in which the experimental line was put up. The measurements were taken from time to time during the 8 months period i.e. from Jany to August 1965. Fig.3.18 shows the earth resistivity variations for the above mentioned period. The highest temperature was observed in the month of June, the soil was almost dry and hence the earth resistivity was the highest.



Average Earth Resistivity $\rho = 2\pi a R$.

MEASING RESISTIVITY OF THE EARTH
(a)



MEASURING RESISTANCE OF EARTH ELECTRODE.
(b)

Fig. 3.17

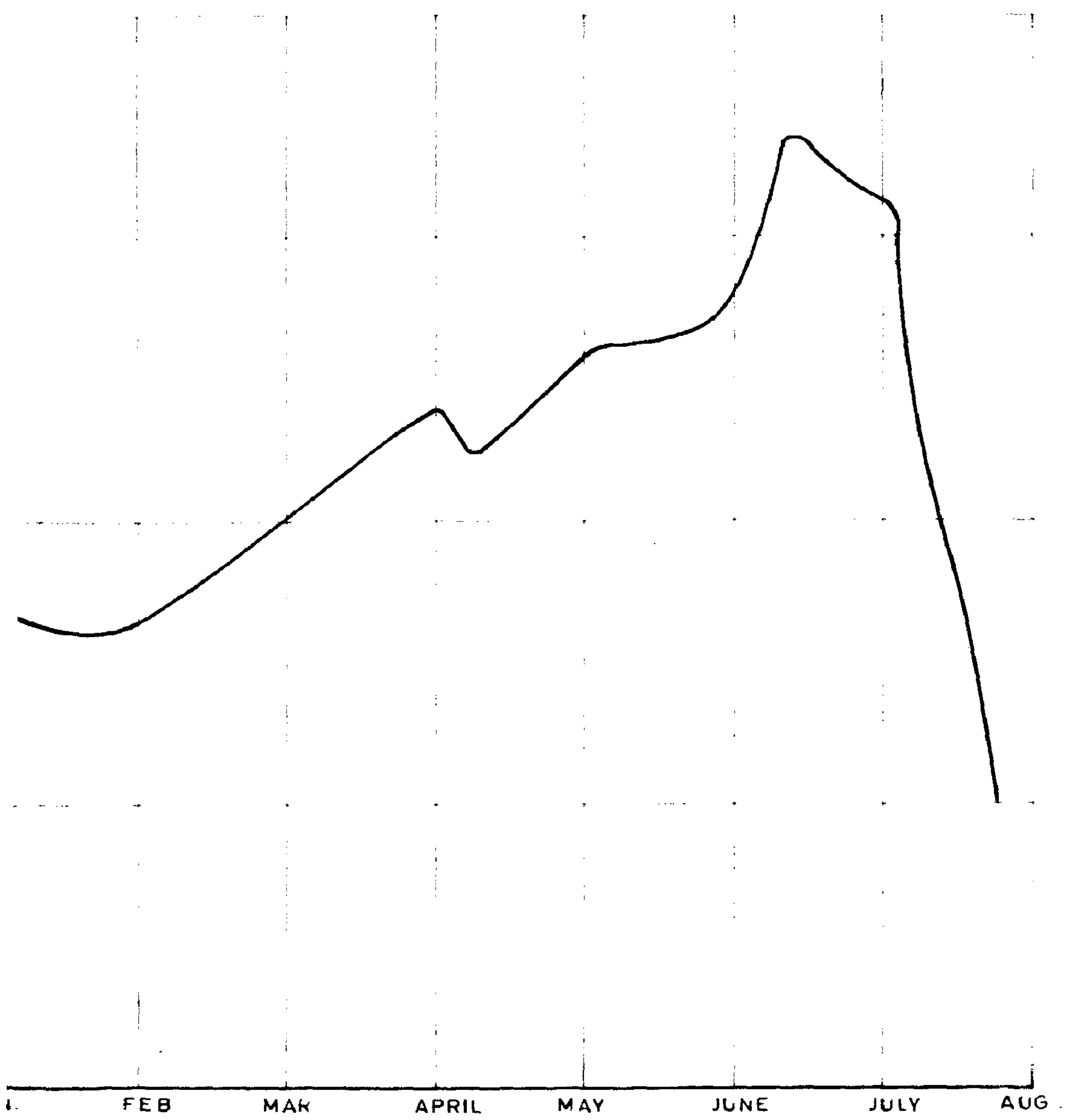
On the other hand in the month of July measurements were taken when the soil was very much wet after a continuous rain for two days.

3.24 Measurement of Earth of resistance of Ground Electrodes:

The resistance to earth of the different electrodes, installed at the receiving and sending end of the line, was measured by the same I M U earth tester which used for measuring earth resistivity but connected as shown in fig.3.17(b). The results obtained are indicated in the following Table.

TABLE

Type of Electrode Driven pipe (1)	Length (2)	Measured Value of resistance to earth of the electrode in ohms. (3)	Calculated value of resistance to earth of the electrode in ohms. (4)
	(in meters)		
Driven pipe 3.6 cm(1.5")dia.	1	49.85	48.5
	2	30	28
	3	21	20.2
	4	15	15.95
	(Spacing between the x.. pipes)		
Two driven pipes in parallel - length of each pipe - = 2 meters.	1 meter	18.6	17.7
	2 "	16.8	15.4
	3 "	14.4	14.8
	4 "	14	14.5
	6 "	13.8	14.35
Three driven pipes on equilateral triangle and connected in parallel length of each pipe =2 meters.	1 "	15.5	14.2
	2 "	12.2	11.3
	3 "	11.0	10.5
	4 "	10.8	10.0
	6 "	10.0	9.8

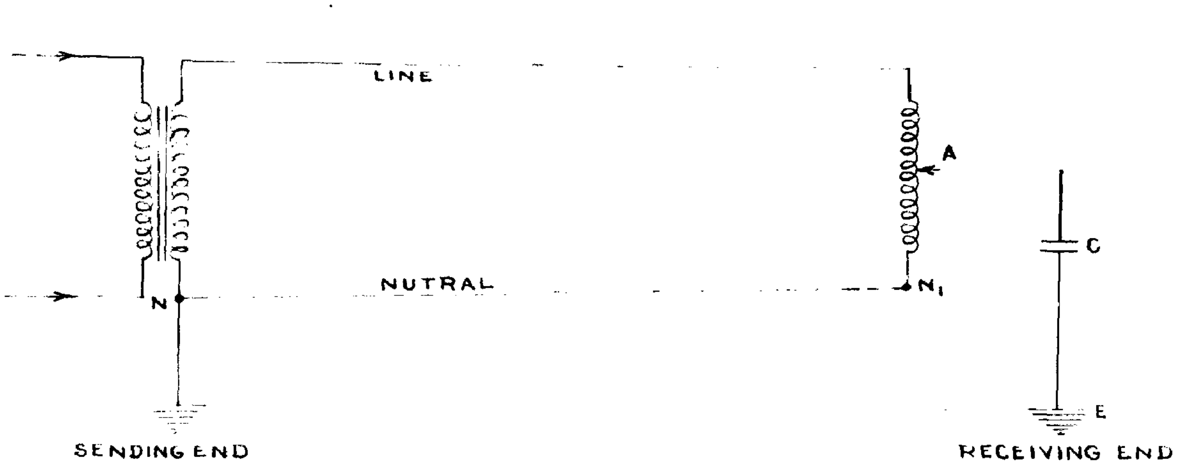


18 EARTH RESISTIVITY MEASUREMENTS FOR THE SITE OF EXPERIMENTAL SINGLE FACE SINGLE WIRE LINE

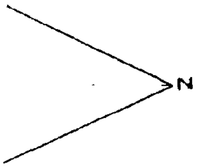
(Table contd -

(1)	(2)	(3)	(4)
<u>Four Driven Pipes</u> on square and in parallel - Length of each pipe = 2 meters.	1 Meter	12	11.2
	2 "	10.[illegible]	9.9
	3 "	9	8.3
	4 "	8.2	7.96
	6 "	8	7.82
Four driven pipes in straight line and in parallel.	1 "	11.8	
	3 "	10.3	
	4 "	8.5	
Rectangular M-S Plate buried vertically depth- 1.5 m	1 x 1 M	28.5 Ω	26.48 Ω
Two M.S.plates of in parallel - distance between the centre of the plates.	1 x 1 m 2 meters.	16 Ω	15.6 Ω
<u>Horizontal Buried wires</u> buried 40 meter below the surface.	20 meters	7.8	6.48
	10 meters	12.92	11.2
	30 meters	40.8	42
Two copper wires buried at angle and in parallel.	10 meters 45°	10.1	9.6
Two copper wires buried at angle with each other.	90°	9.8	
Two buried wires in parallel.	20 meters	4.2	3.85

From the above table it can be seen that the calculated values of the earth resistance and the measured values are nearly equal.The higher resistance during the experiments may be due to improper contact of the soil with the test electrode.



CIRCUIT DIAGRAM FOR MEASUREMENT OF RESISTANCE AND RESISTANCE OF GROUND RETURN PATH.



[illegible] - Voltage drop across capacitor

[illegible] - Voltage drop across earth return (including local resistance of the ground electrodes at both ends)

[illegible] - Voltage drop across the capacitor and earth return.

[illegible] - Voltage drop across the resistance component of earth return.

[illegible] - Voltage drop across the reactive component of the earth.

FIGURE 3.19

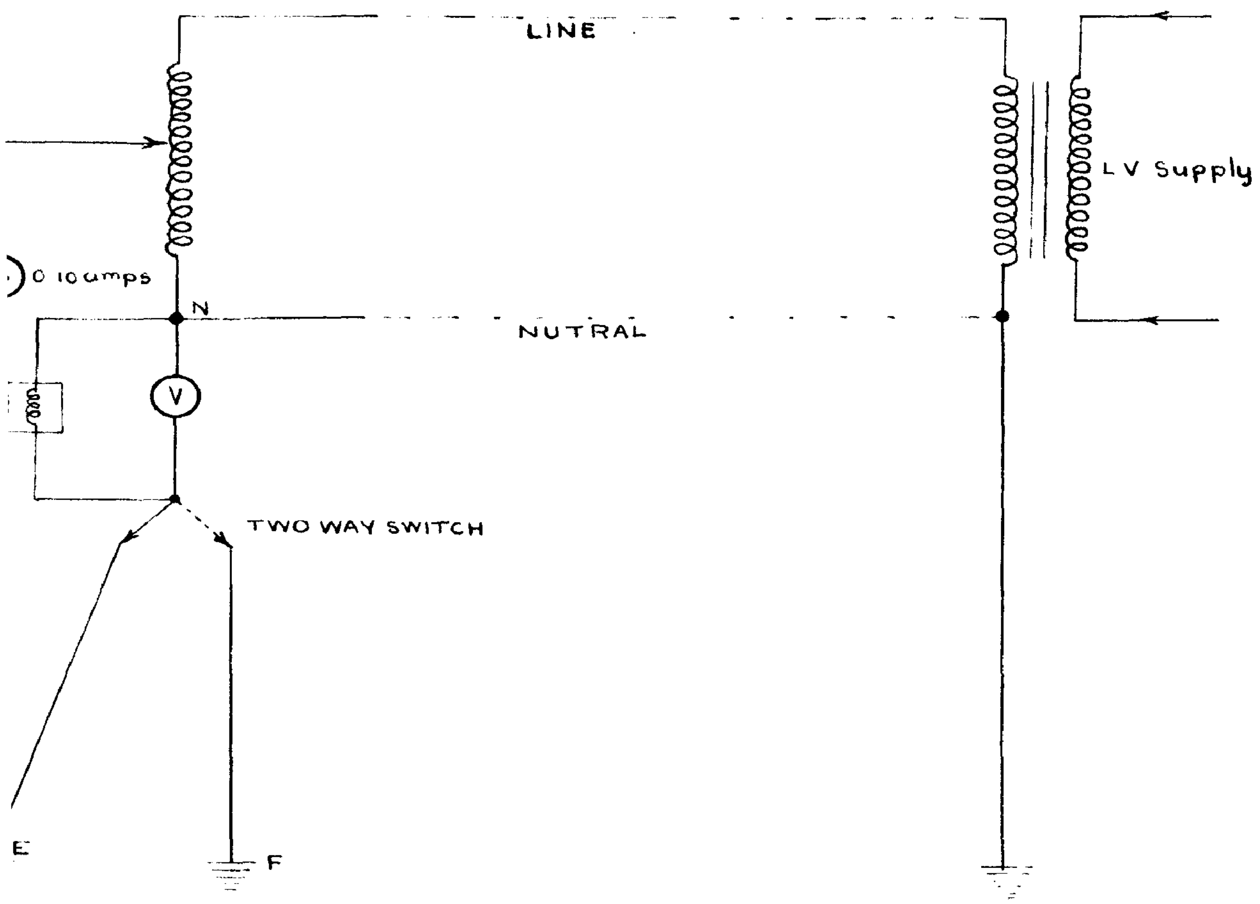
3.2.5 Determination of Resistance and Reactance of Earth Return Path

Fig.2.18 B shows the circuit diagram for measurement of resistance and reactance of the earth return path. One wire was connected to the neutral of the transformer at the sending end and brought at the other end. A variable ratio auto-transformer was connected to the ground through a capacitor.

The voltage drop between AE AN and EN was measured with the vaccum tube voltmeter. The Ground current was va-ried by adjusting setting of the auto-transformer. Vector diagram shown in the figure, was drawn for each and the corresponding values of resistance and reactance of the earth return path wire determined. The total local resistance at both the ends was measured and was found to be 9.4 Ohms. The results are indicated in the following table.

Current Amps.	Capacitance uF	Voltage drop between AE	Voltage drop between NE	Voltage drop between AN	R_T	R_C	R_S	X_S ohm
1	250	12.5	9.5	15.5	.9.45	9.4	0.05	0.1
2	250	25	19.0	30.5	9.50	9.4	0.1	0.12
3	250	37	28.5	46.5	9.55	9.4	0.10	0.1
4	250	49	37	61.5	9.45	9.4	0.05	0.1
5	200	31.5	19.5	37	9.45	9.4	0.1	1

R_C = Local resistance at both the ends.
R_T = Total resistance of the earth return path.
R_S = Resistance of the soil = (R_T - R_C)



CIRCUIT DIAGRAM FOR MEASUREMENT OF RESISTANCE OF GROUND RETURN PATH

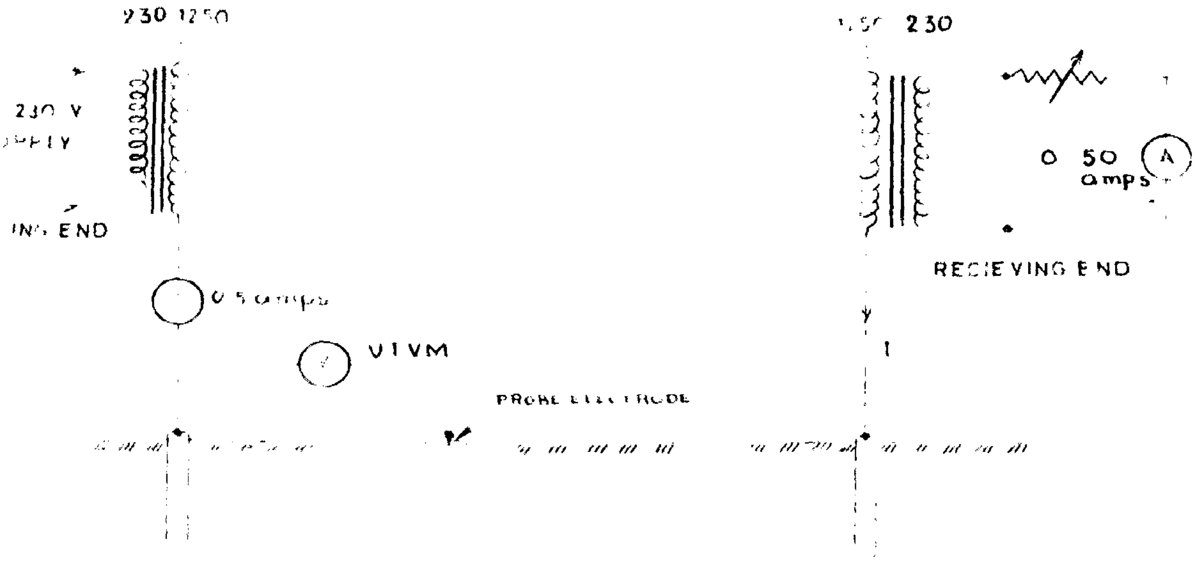
Fig 3.18A

Measurement of Resistance of the return path :

Fig. 2.18 A indicates the another method for determining the resistance of the return path. Low voltage supply was given to the sending end transformer. At the receiving end, the adjustable point of the auto-transformer was connected to the ground E through ammeter and current coil of the wattmeter. F is another earth terminal removed about 100 feet from E. The current was varied by adjusting the settings of the auto-transformer. The results arè indicated in the following table.

Current	Measurement to E Terminal			Voltage between G and E	Measurement to F Terminal			Local Resistance at G	Resistance of the earth retu path
I	V_1	W_1	$R_1=W_1/I^2$	V_{GE}	V_2	W_2	$R_2=W_2/I^2$	V_{GE}/I	$R_s=R_1-(R_2+R_E)$
2	30	60	15	27.0	8	5.5	1.38	13.5	0.12 Ohm.
3	44	132	14.67	40	9.5	115	1.28	13.33	0.05
4	60	240	15	54.5	12	21	1.31	13.62	0.06
5	74	368	14.72	67.0	14	32	1.26	13.4	0.06

The results obtained from the above two methods show that the resistance of the earth return path is 0.06 Ohm (average) and the reactance as 0.1 Ohm. The measured values of the resistance and reactance of earth return path are greater than the values found out analytically.



CIRCUIT DIAGRAM FOR

ASUREMENT OF POTENTIALS ON THE EARTHS SURFACE

Fig 3.19

3.26 Measurement of surface potentials around the Electrodes:

Fig 3.19 shows the circuit diagram for the measurement of surface potentials around the electrode. Probe electrode i.e. M.S. nails were used to simulate the surface contact with the earth.Voltages were measured with the vaccum tube voltmeter.

Experimental Results and Discussion:

The surface potential distribution for the single driven rod, rods in multiple, plate electrodes and buried horizontal wires, was studied . The results obtained are shown in Figs 3.20 to 3.26 for convenience all the surface potentials were measured for one ampere ground current.In all the surface potential curves, distances from the reference point towards the remote electrode along the reference line shown dotted on each figure, are plotted on x axis and the surface potentials on y axis .The resistivity of the earth was measured by I M V earth tester and was found to be 70 ohm meters.

From all the curves shown in the figures it can be seen that nature of the distribution of surface potential around the electrode is similar to that of obtained by model tests. Instead of discussion again the results obtained for each case which has already been discussed in 3.1, here the results obtained by both the tests are compared.It has been seen in that the relation of the surface potentials for the model and prototype is

$$\frac{EP}{EM} = \frac{P_p}{PM} \times \frac{LM}{LP} \times \frac{IP}{IM} \quad ----(3\cdot 8)$$

For the model to actual ratio of 1 : 40, model ground current IM = 0.1 amp and Im (field) = 1.0 amp

$$\frac{EP}{EM} = \frac{P_P}{P_M} \times \frac{1}{40} \times \frac{1}{10} \quad ---- \quad (3.9)$$

$$= \frac{1}{4}\,\frac{P_P}{P_M}$$

Taking the specific case of single driven rod of 2 meters length, resistivity of the electrolyte during the test-17.0 ohm meters and the resistivity of the earth as 70 ohm meters.

$$\frac{EP}{EM} = \frac{70}{17} \times \frac{1}{4} = \frac{70}{68} \quad ---- \quad (3.10)$$

From this relation the surface potentials E_P were determined for this particular case and were compared with the surface potentials obtained during the field tests as shown in the fig. 3.25 Similarly results obtained for other cases can be compared.

From this figure it can be seen that the surface potentials obtained by model tests are less than the actual potential obtained by field tests. This difference in the two results may be due to error in measurements , non-homogeneity of the soil and some error due to leakage of electrolyte through the tank walls. However, in general the results obtained from model tests nearly agree with those obtained from field tests and can be taken as a guide to study the gradient problem.

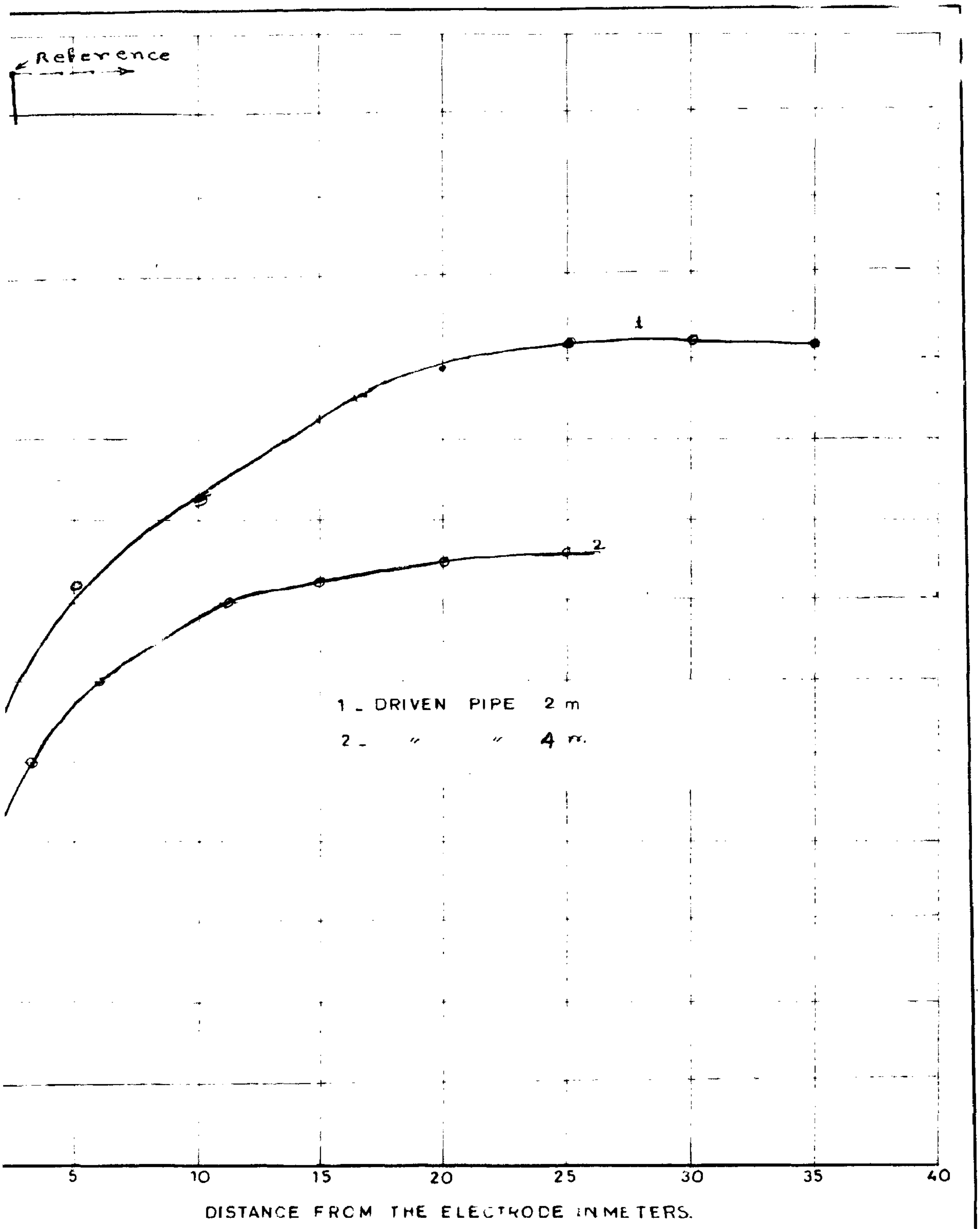


FIG.3.20 SURFACE POTENTIAL DISTRIBUTION FOR DRIVEN PIPE.

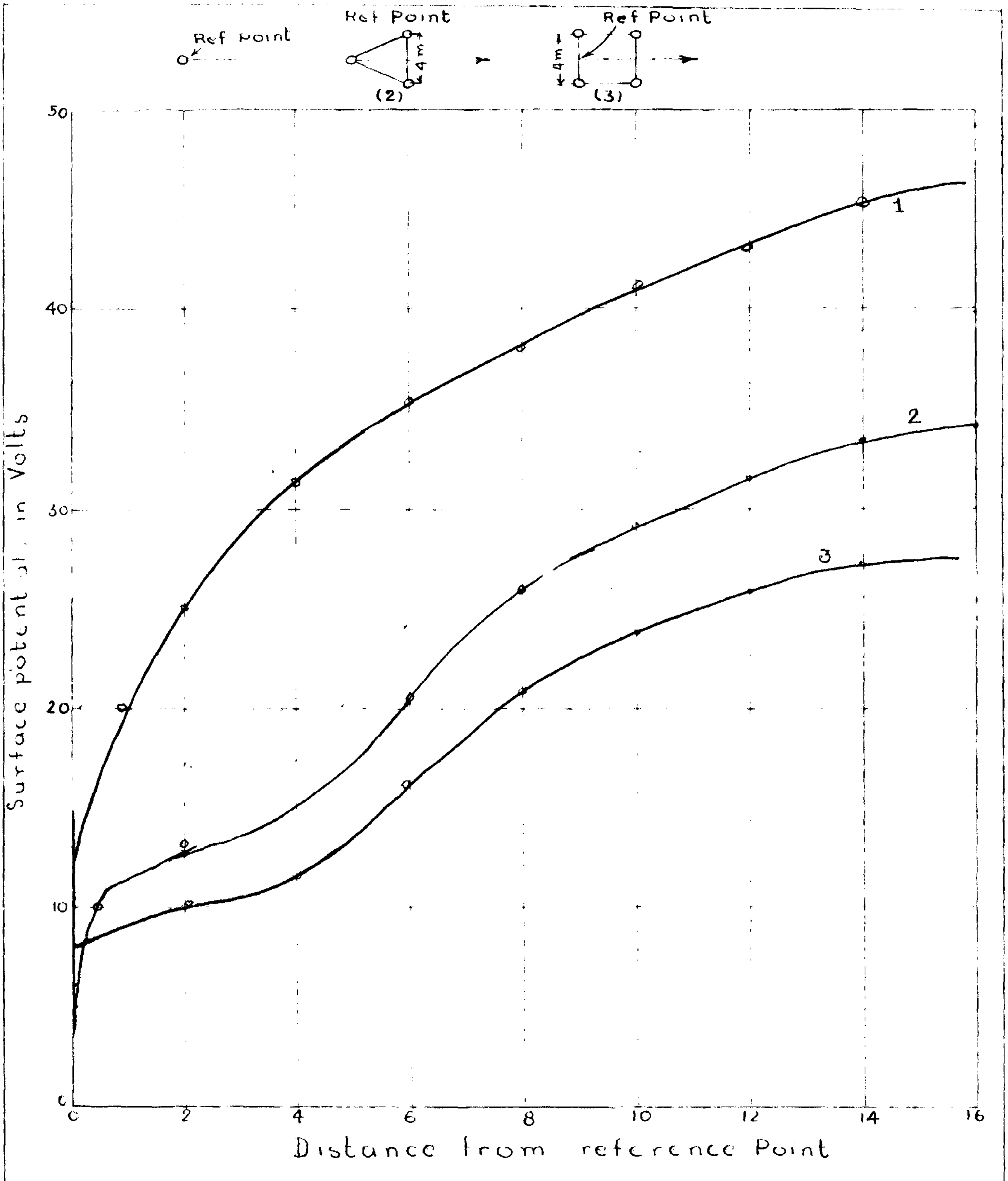


Fig. 3.21 EFFECT OF CONFIGURATION

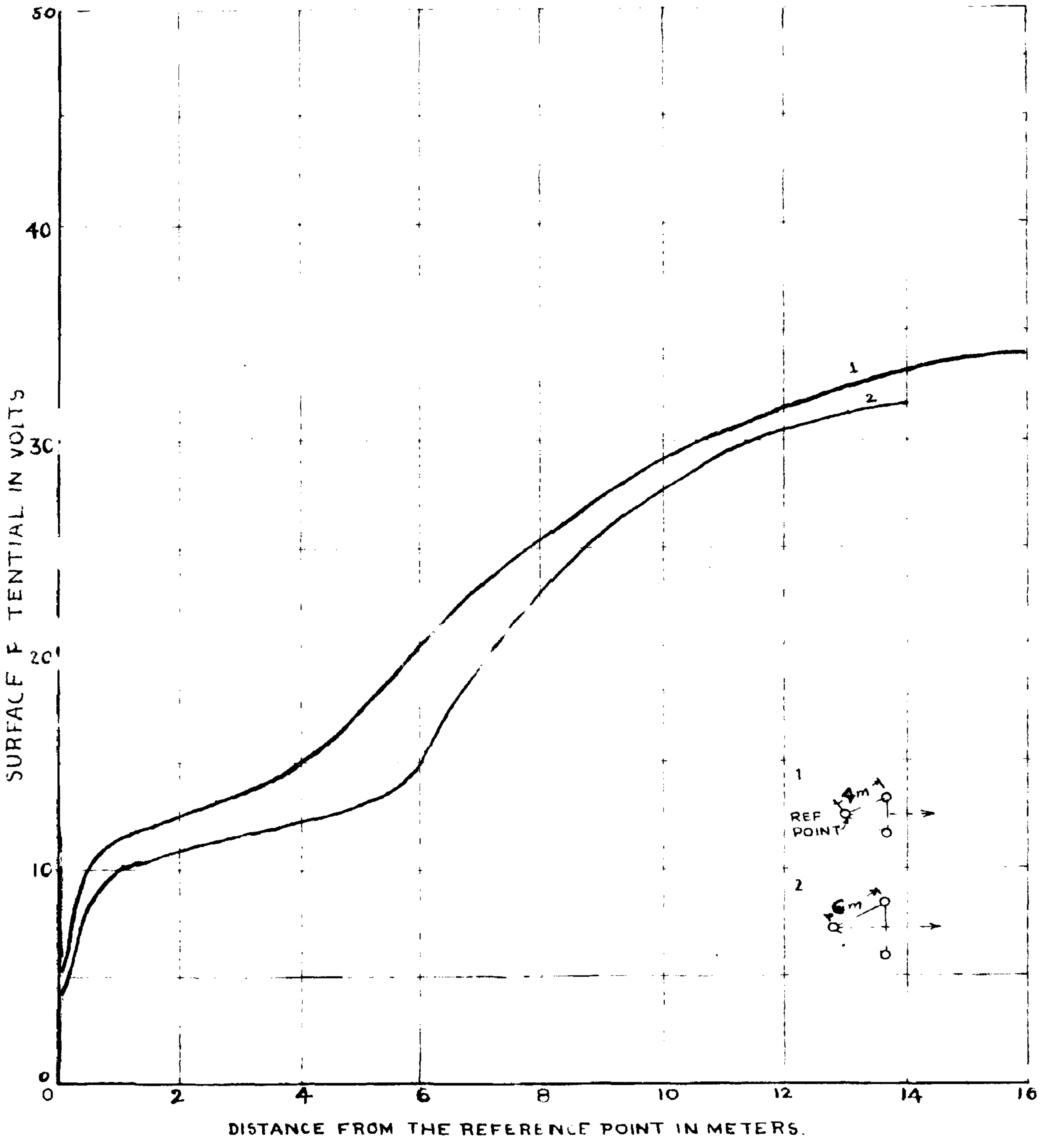


FIG.3·21b SURFACE POTENTIAL DISTRIBUTION

EFFECT OF DISTANCE OF SEPERATION.

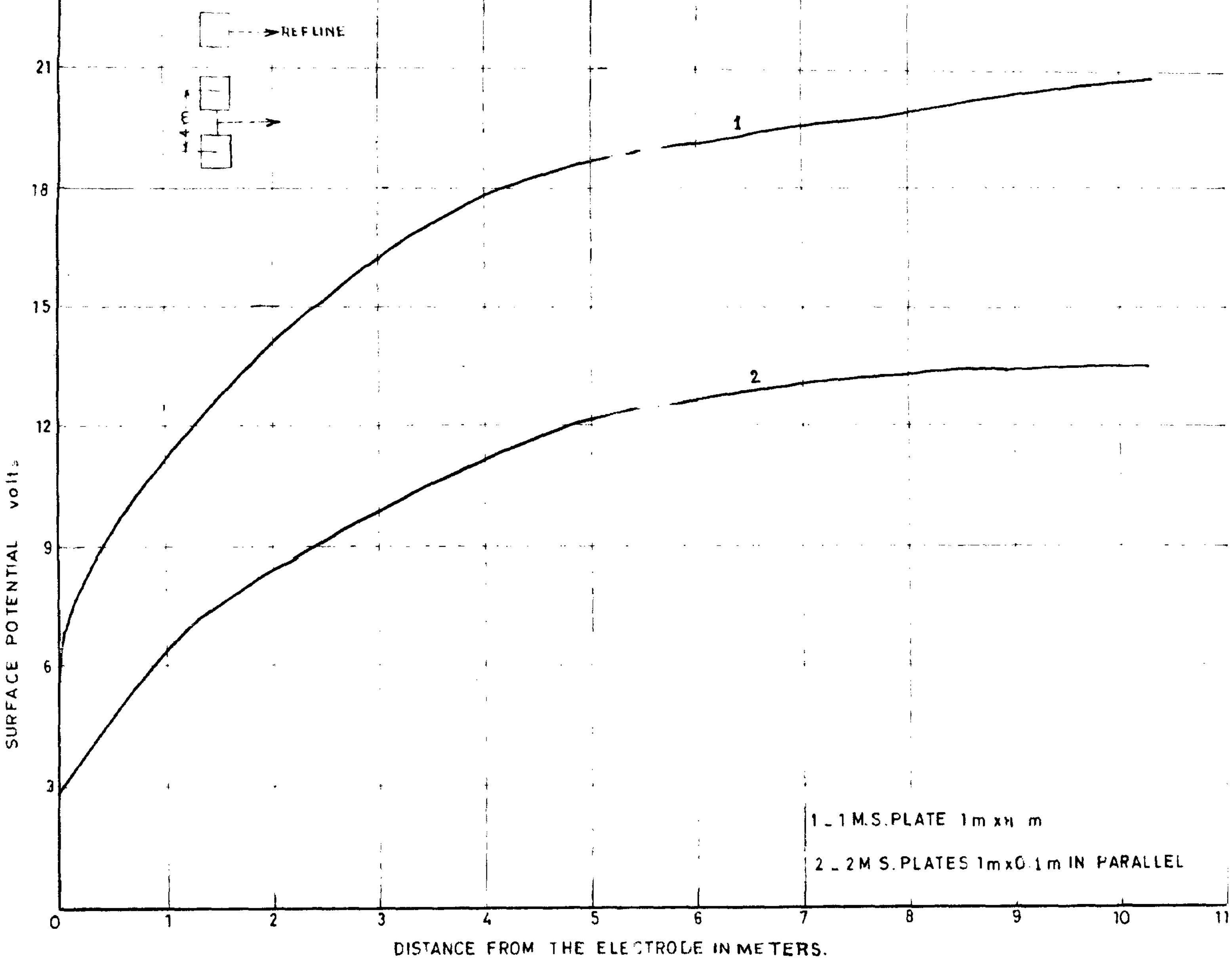


FIG.3.22 SURFACE POTENTIAL DISTRIBUTION FOR PLATE ELECTRODE

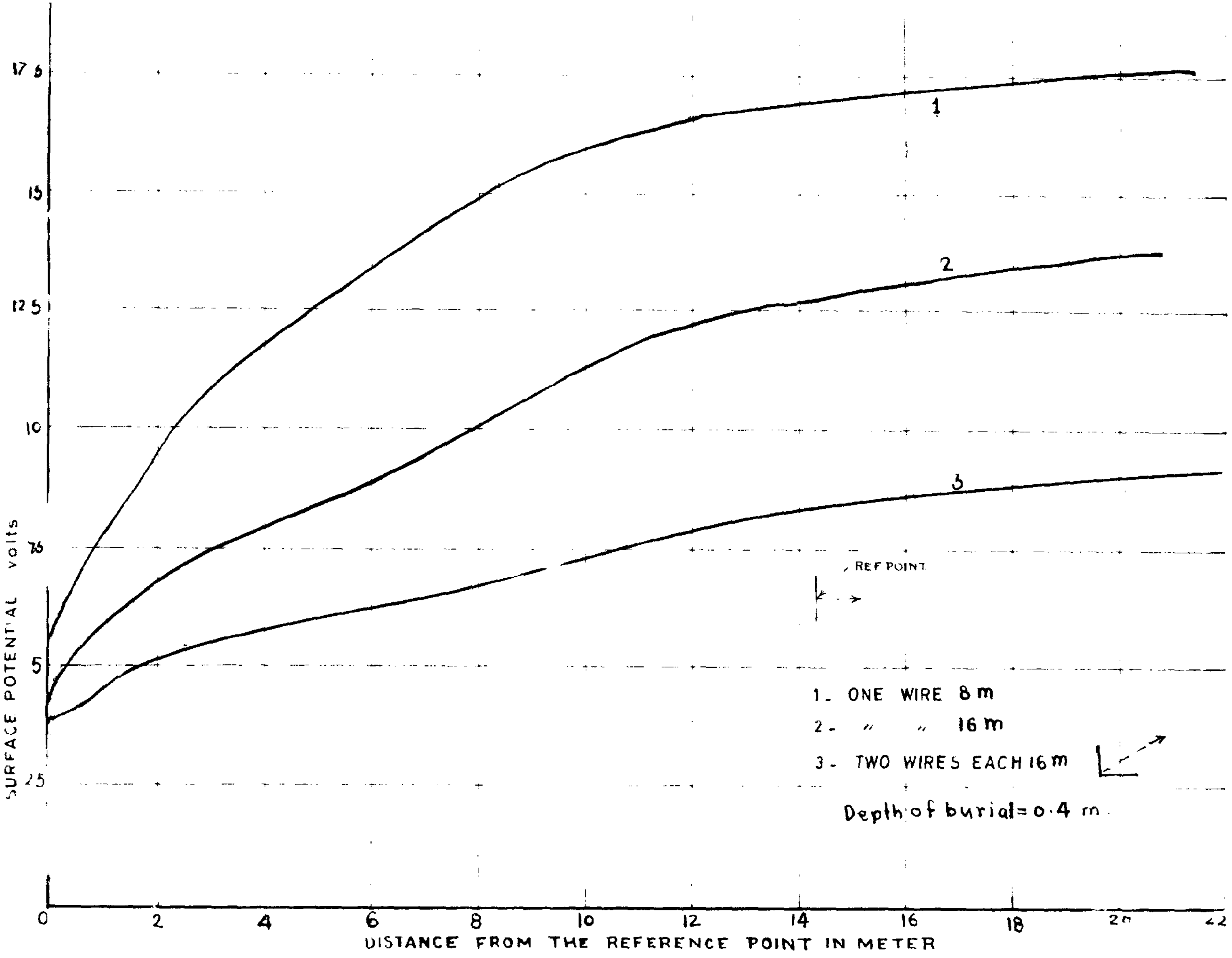
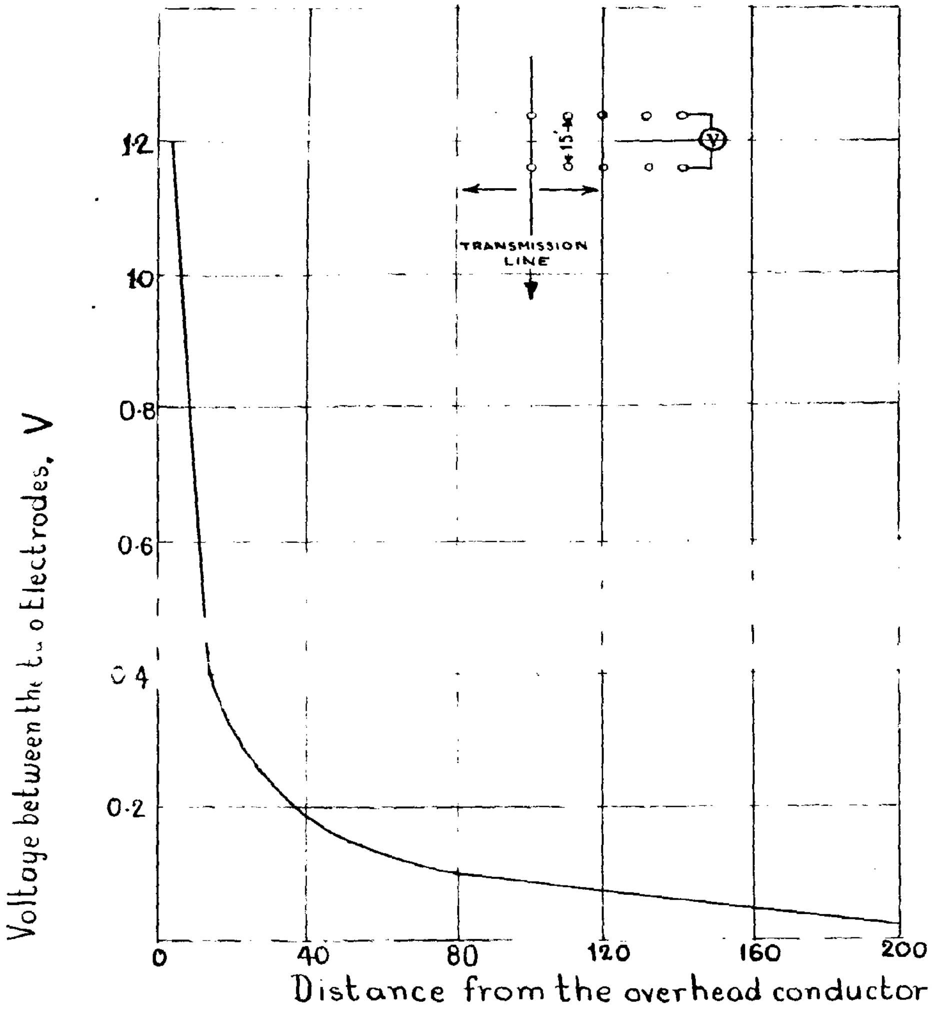
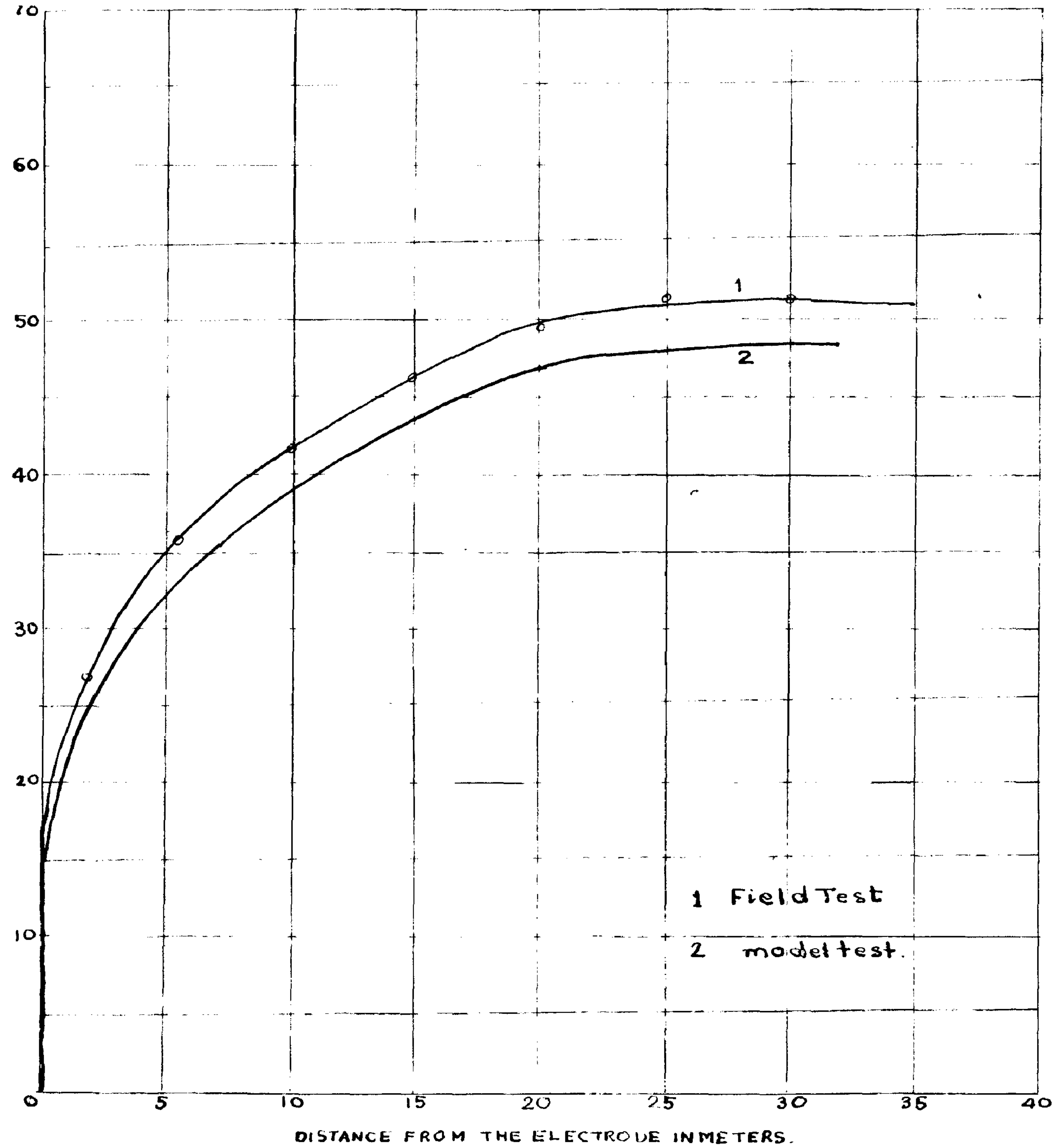


FIG.3.23 SURFACE POTENTIAL DISTRIBUTION DUE TO BURIED HORIZONTAL WIRE



BEHAVIOUR OF CURRENT FLOWING IN THE EARTH.

Fig 3 24.



COMPARISON OF THE TEST RESULTS
FOR SINGLE DRIVEN ROD.
Fig 3.25

CHAPTER - 4

PROTECTIVE SCHEMES

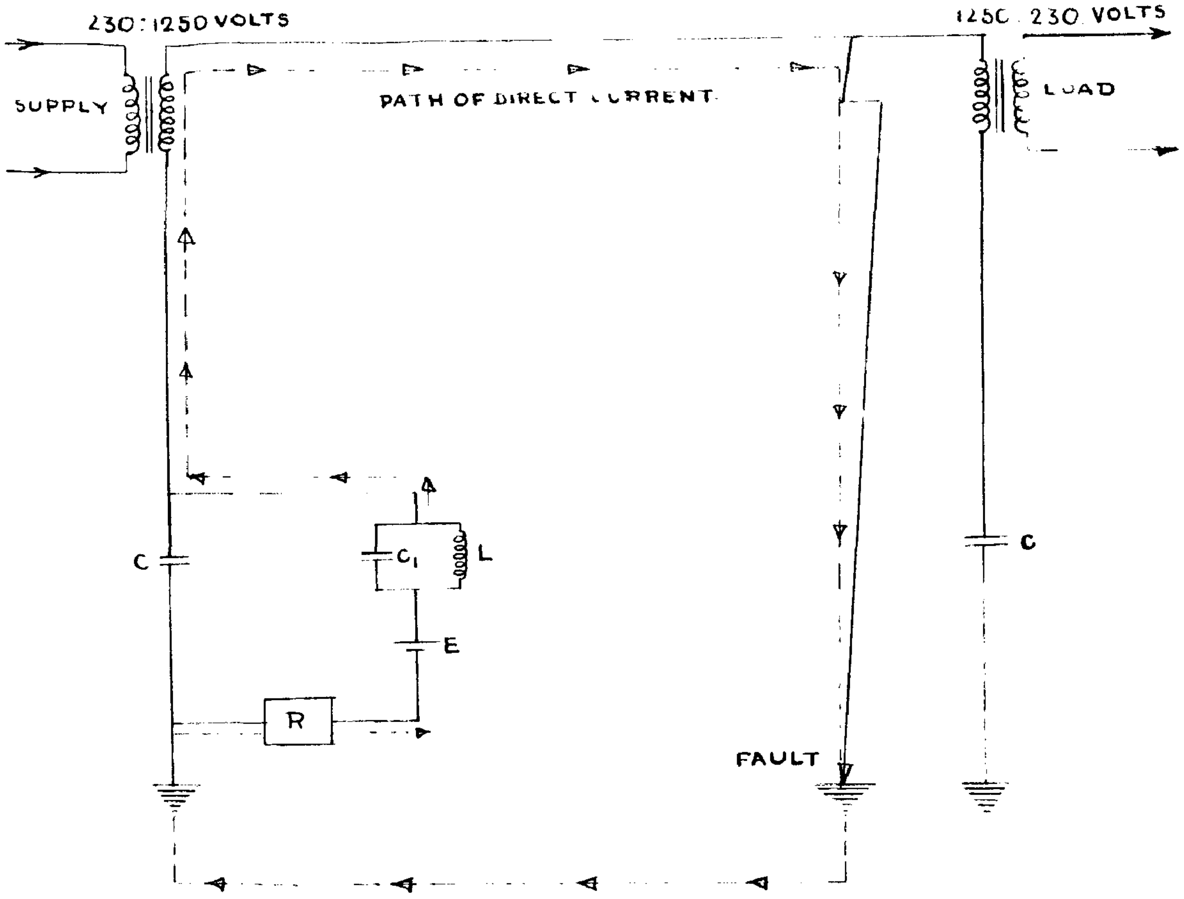
PROTECTIVE SCHEMES

4.1 This system can be protected for over current and tripping or fusing would occur depending on the Relay/Fuse setting and the nature of the severity of fault. The chances of fault on such lines will be much less in comparison to other usual lines, as there will be no chances of short-circuit between the conductors or with cross arms. Faults most likely to occur on such lines would be earth-faults. It is also essential to provide protective scheme for preventing potential build up near ground electrode.

4.2 Protection against high resistance earth faults:

4.21 If there is a high resistance earth fault on such line then the fault current would be lesser than the load current and the fuse would not blow or the over-current relay would not trip and the fault would continue to be load on the line. However, it is practicable to provide an effective protective scheme against such faults on this line.

This scheme is illustrated in Fig. 4.1. D.C. potential is super-imposed on the power line. D.C.Source and the relay is connected in series with a tuned circuit or a highly inductive choke, to reduce the alternating current flowing through the relay. Capacitor is connected between ground and ground terminal of the transformer at the receiving end as well as at the sending end. These capacitors block the flow of D.C. from the normal path of the current. In normal



C= 20μF C₁ 10μF L 1H E 12 VOLTS.

PROTECTIVE SCHEME FOR HIGH RESISTANCE EARTH FAULT

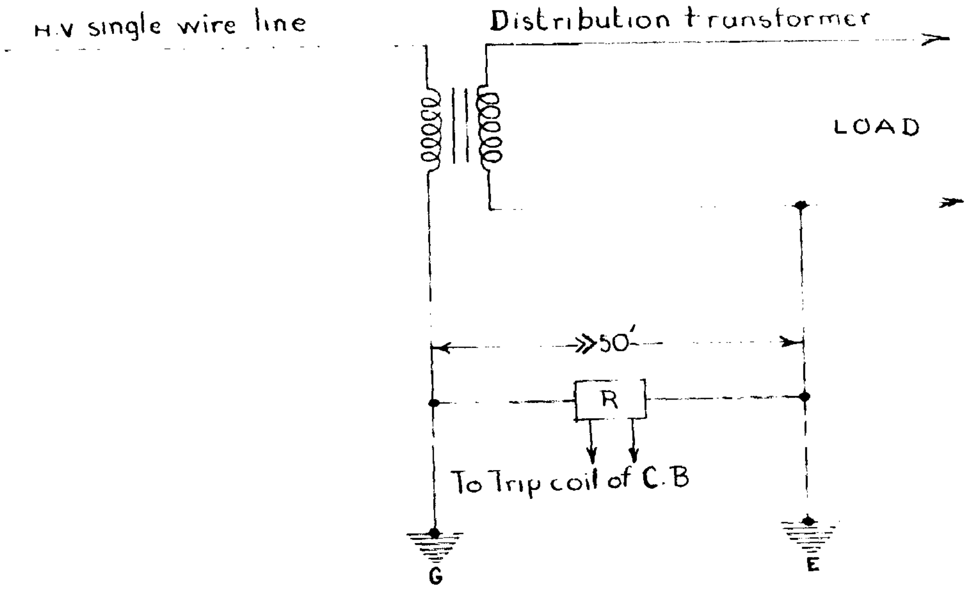
Fig 4.1.

conditions the path for the d.c. will not be completed, but in case of fault the circuit will be completed through the fault to ground causing the relay for its operation. The relay will trip the circuit breaker.The current flowing through the relay will be small depending upon the resistance offered to the fault .Hence the relay can be highly sensitive one with the low setting of the order of microamperes.

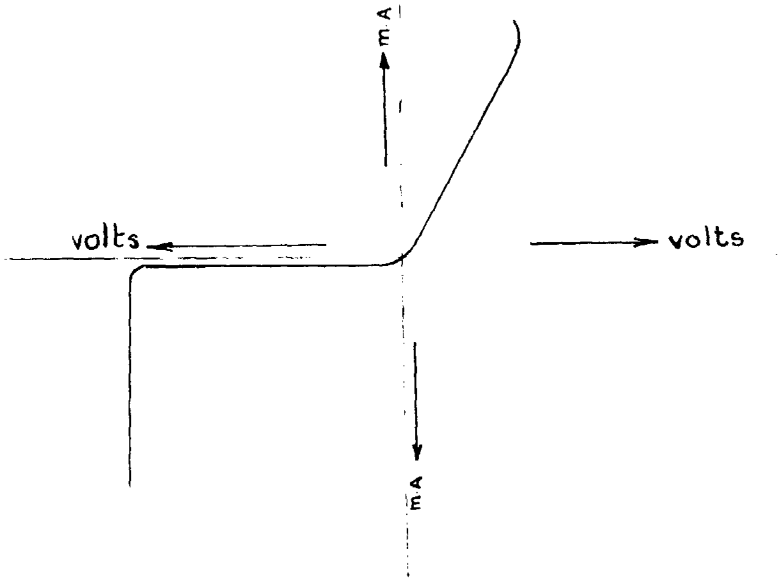
The above scheme was actually tested on the experimental single phase line using earth return,erected in the University premises. With the connections shown in fig. an earth fault was created at the receiving end. In place of the relay ammeter was used to indicate direct current flowing during the fault.A battery of 12 volts was used as a source of d.c. potential. Before the earth fault the current flowing in the ammeter was zero.However, with the earth fault at the receiving end the ammeter indicated 5.5. milliamps. This much current is sufficient to operate the relay having pick-up of 5 milliamperes.

For putting this scheme in actual practice it may be necessary to have large values of d.c. voltages. This can be obtained by using the rectifier for which the supply can be taken from the transformer itself.

4.22 Protection against such earth faults may also be provided by using carrier. If an unmodulated voltage wave of any frequency, may be voice freqhence, is superimposed on the line at the sending end a wave trap being provided at each



R- OVER VOLTAGE RELAY.
(a)



ZENER DIODE CHARACTERISTIC.
Fig 4.2 (b).

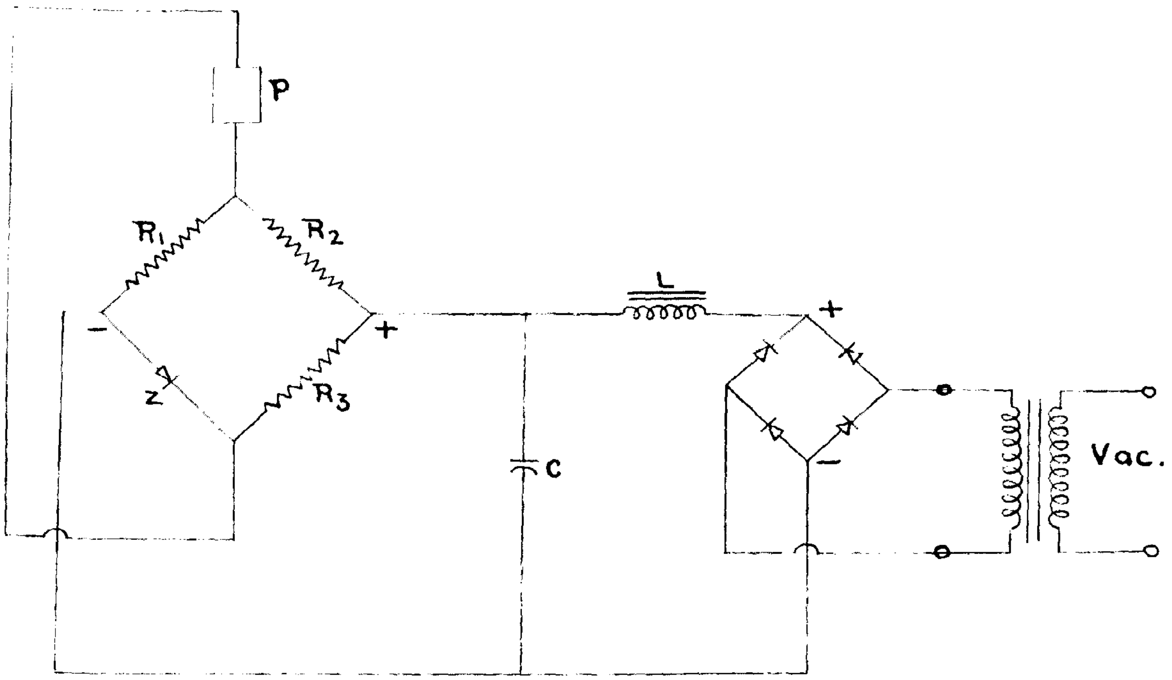
transformer installation, then in normal course,there will be virtually no load on the carrier.However if a ground fault develops any where on the line, this will be a loan on the line as well as carrier and can be detected as such by a detecting apparatus at the sending end.This can be made to operate a relay which will trip the line eventually. However, this scheme will be much handicapped by the high cost in view of the economics to be achieved.

4.3 Protection scheme for preventing potential hazard due to build up of potential near the earth electrode.

4.31 Potential hazard due to build up of potential near the earth electrode can be prevented by using a over voltage relay between the main earth and the auxiliary earth G shown in the fig 4.2. The auxiliary earth electrode G is located about 50' away from the main earth.The over-voltage relay R is adjusted for predetermined voltage between E and G. If due to increase in ground current or some other change in conditions of the earth the voltage of either of the electrode is raised above the setting of the relay R, it will operate which eventually will trip the line.Electromechanical or static relays can be used for such arrangements .

4.32 STRATIC OVER VOLTAGE RELAY

A new simple static over-voltage relay has been developed in the laboratory Fig. 4.3 shows the basic circuit of the relay.Alternating voltage Vac is fed to the bridge rectifier through the potential transformer. The bridge rectifier consists of four single phase metal rectifiers . The



$L = 1.0\,H$ $C \cdot 1000\,\mu F$. $R_1 - 575\,\Omega$. $R_2 = 25\,\Omega$. $R_3 = 970\,\Omega$

Z · Zener diode   P – moving coil polarised relay.

STATIC OVER VOLTAGE RELAY.

Fig 4.3.

rectified out-put is smoothed by using a filter circuit consisting of capacitor and inductor of the values indicated in the fig 4.3 .The filtered out-put is fed to the bridge net--work. In one branch of the bridge the zener diode has been connected. Here the purpose of the zener diode is to provide a reference voltage.It has been seen that a bridge circuit including a reference voltage gives greater sensitivity.

Zener diode is a special type of silicon diode which maintains a reverse voltage over a wide range of reverse durrent which is sufficiently constant. The characteristic of such diode is shown in the fig 4.2. The reverse current is constant upto a particular value of the reverse voltage.When the reverse voltage exceeds this value which is termed as the break down voltage, a small increase in the reverse voltage causes a large increase in the current.This property of the zener diode has been used to provide the reference voltage. The specifications of the Zener diode used are as follows :

Zener diode IOZ -27
Equivalent 2 x 27
Zener Voltage - 25 volts
Voltage tolerance- 5%
Zener current - 40 M A without heat sink
-320 MA with heat sink
Power dissipation- 10 watts.

For the predetermined value of Vac the bridge, consisting of the zener diode and the resistance shown in the fig is balanced by adjusting the resistances R_1 R_2 and R_3 Under the balance conditions there is no current flowing through the relay. However, if Vac exceeds this pre-adjusted value, then an unbalance current of appreciable magnitude flows through the relay causing it to operate. For the values of the resistances shown in the fig. 4.3 the bridge was balanced for Vac = 46 volts.The relay was operated for 4% increase in the voltage .The setting of the relay can be adjusted by proper selection of the bridge resistances.This relay is more simple and cheaper than the electro-mechanical relays.

4.33 The adequacy and permanence of this ground connection may also be ensured by the use of differential relay between two parallel ground electrodes, which may be made to trip the circuit or give an alarm in case of a failure of their ground electrode.

CHAPTER - 5

PRACTICAL ASPECTS OF THE SYSTEM

PRACTICAL ASPECTS OF THE SYSTEM

5.1 LOADS IN THE RURAL AREAS:

In the rural areas the first and obvious attraction would be for lighting primarily.Despite the benefits of electricity, no body in the countryside at present income levels could use it for any other labour saving devices. Use of electricity in rural areas for fans, heating and small pumps for domestic use is limited since the consumption for domestic purposes depends on the standard of living of the people. The connected load per consumer in rural areas is about 100 watts as compared with 500 watts in urban areas. Public lighting load offers a good scope for electrification.

Electric Flour Mills can displace the manually operated flour mills in the rural areas. The general power requirement for the flour mills varies from 5 HP to 10 HP.

Irrigation is becoming the important rural load due to " Grow More Food " Campaign started by the Government.The size of the pump required for irrigation from wells depends on the area to be irrigated ,nature of the soil and the crops, besides depth of water level in the well. Average H.P of pumps required for irrigation from wells is indicated in the table.

TABLE

Acreage covered by the pump depending upon the type of crop.	Average H.P. of the Pump required.			
	40'	60'	80'	Water Head.
15-25	3	3	5	
26-50	3	5	7.5	
51-80	5	7.5	10	

3 H.P. and 5 H.P. motors are most commonly used.

5.2 POWER SUPPLY FOR MOTORS:

5.2.1 Use of Single Phase Motors -

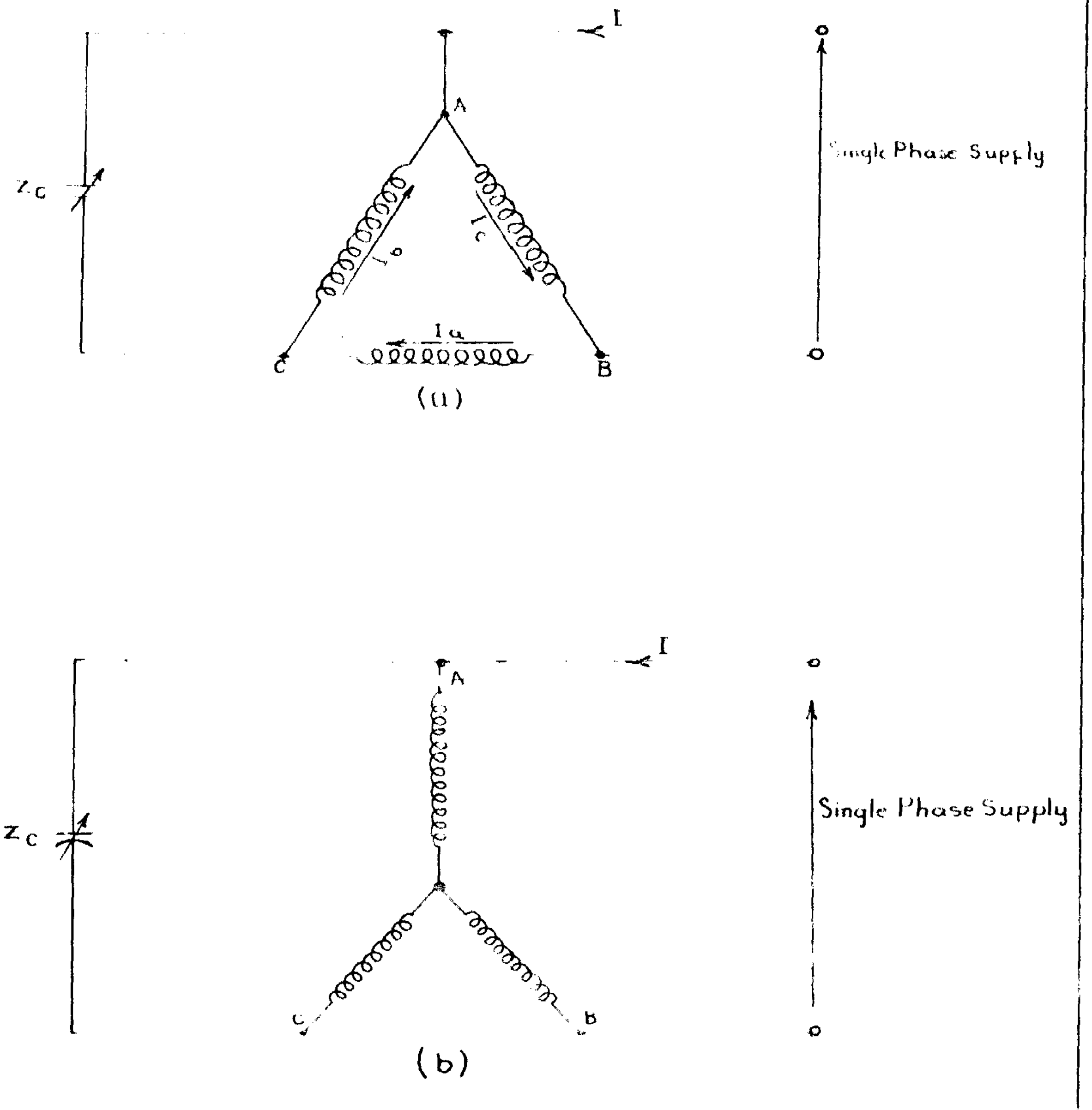
The single phase motors which can be supplied by single phase single wire system can be used to meet the above loads. Generally single phase capacitor motors are preferred. Single phase motors cost more than the 3 phase motor and have poorer performance. Though single phase motors cost more than 3 phase motors they are cheaper than the corresponding disel engine power. Moreover, the total cost of single phase connections to the consumer will be much less than that of 3 phase connection. The extra cost of single phase motors can thus be balanced in economy of the individual consumer.

In India, single phase motors are not available above the small integral horse power sizes. The availability of single phase motors will depend only on the demand (22). This is clearly shown by American experience: (1) Single phase motors can readily be made available upto sizes of 25 H.P. (2) there is strong consumer demand for single phase motors inspite of their higher cost, this will be true ofcourse, especially in areas where single phase supply only is made available. There is no longer the feeling that once existed in U.S.A., and that exists with some now in India, that single phase motors have substantially less reliability than polyphase. With extensive use of motors single phase motors in any size need not be handicapped by lack of reliability. If single phase earth return systems were to be widely applied, the single phase motors required in the rural areas should be made available at reasonable cost.

5.2.2. Operation of 3-Phase Motors on Single Phase Supply:

Where single phase motors are not available, standard 3-phase motors with phase convertor can be used on single phase supply. The operation of three phase induction motor from single phase supply is being studied from the time, the induction motor was invented.However, the interest was in the condition of single phasing and not as practical alternative. During the last two decades,serious study was taken up to find practical alternative and scientists like Haberman (23), Barton and Brown (24) have contributed to this field.

It is well known that when 3 phase induction motor is connected to a single phase supply system, no starting forque is developed. However, the same motor can be run on single phase supply with a suitable capacitor or



3 PHASE INDUCTION MOTOR ON SINGLE PHASE SUPPLY

Fig 5 1

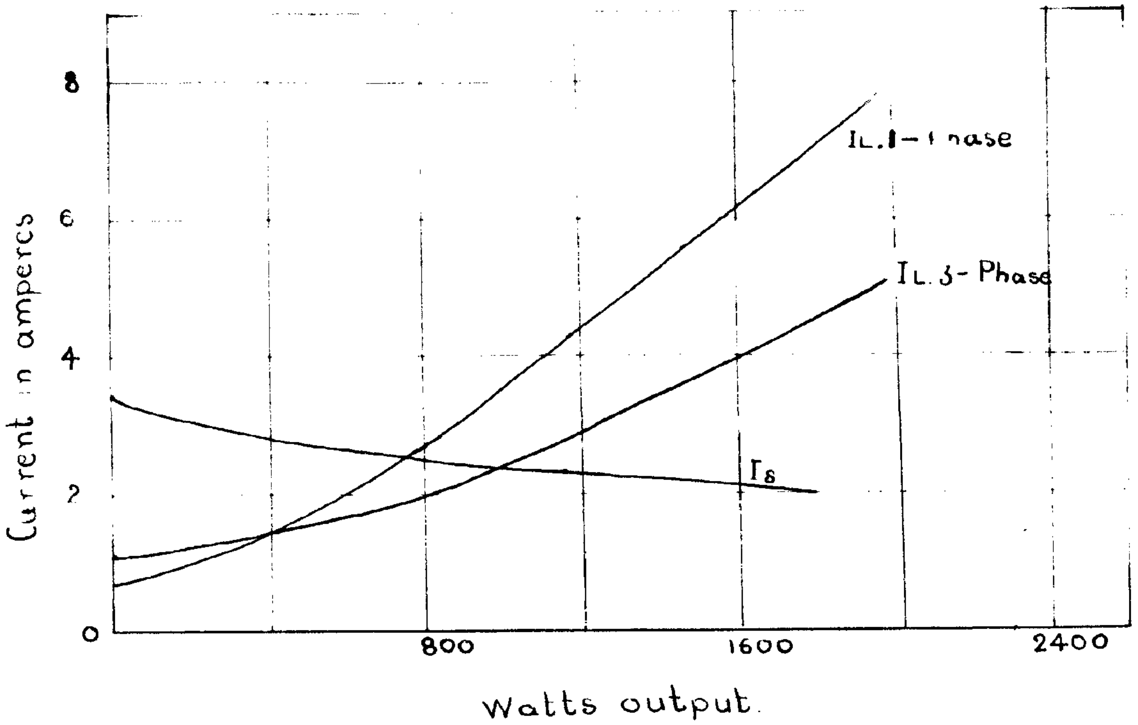


Fig 5.2(a)

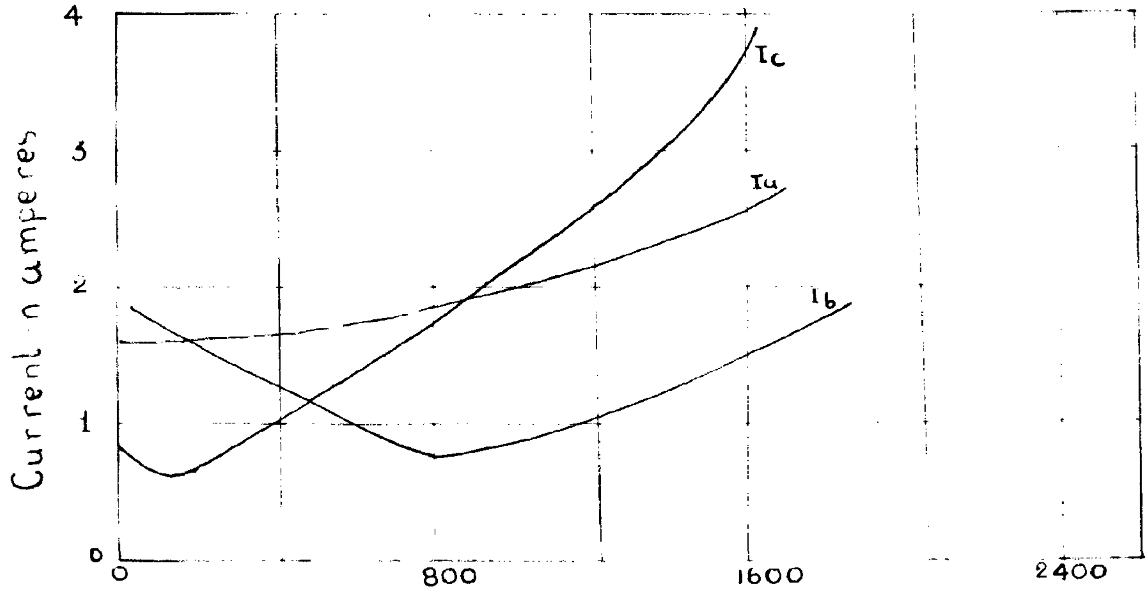


Fig 5.2(b) Watts output.

reactor of proper size to split phases so that the motor may be able to provide rotating magnetic field and be self-starting. Fig. 5.1 represent the primary winding of delta connected and star connected 3 phase induction motor connected to single phase supply with an external static phase converter of the impedance Zc in the circuit. Mathematical analysis of the performance of the motor with the connections shown in fig has been fully investigated by Brown and Jha in their paper on " Operation of three phase motors on Single Phase supply " and also by T.V.Sreenivasan and M.R. Krishnamurthy(25). It has been shown by Brown and Jha that the best type of phase converter from the starting point of view is the pure capacitor. It has also been shown that for the best performance i.e. with minimum unbalance the value of external admittance (i.e. of the phase convertor) should be $\sqrt{3}$ x standstill admittance of the machine. Instead of giving mathematical analysis for the performance of 3-phase motors on single phase supply only some experimental results obtained on 3 H.P., 3 -Phase- 400 Volts 1400 RPM induction motor are produced here.

<u>Performance Characteristics</u> :

Fig. 5.2 shows the performance characteristic of the 3 phase induction motor with 20 UF capacitor shown in the fig. 5.1(a) . From the characteristic curves it can be seen that the line currents and the C- phase currents (across which the line voltage is proposed) are low ~~and~~ at low outputs and increase rapidly after one third fuel load. The

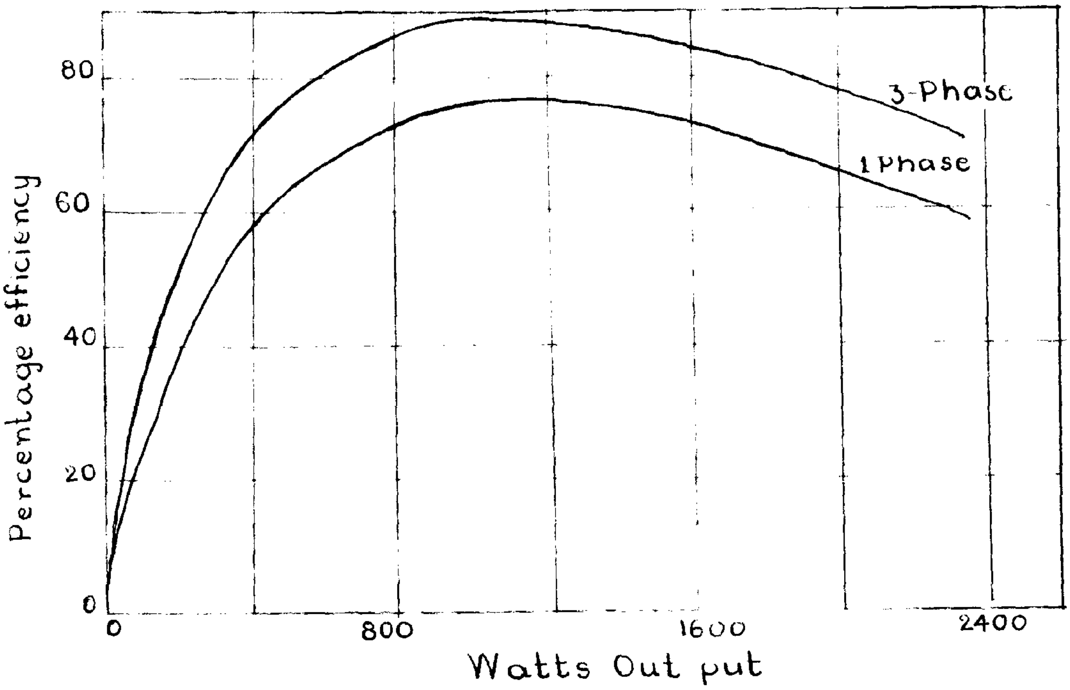


Fig. 5.3(a)

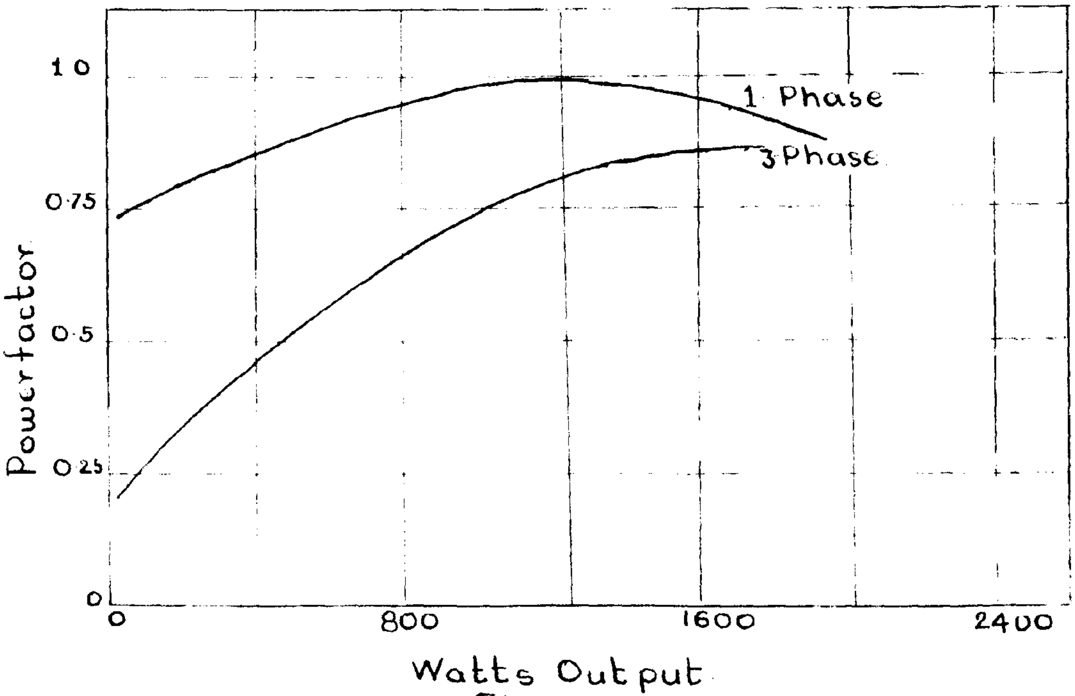
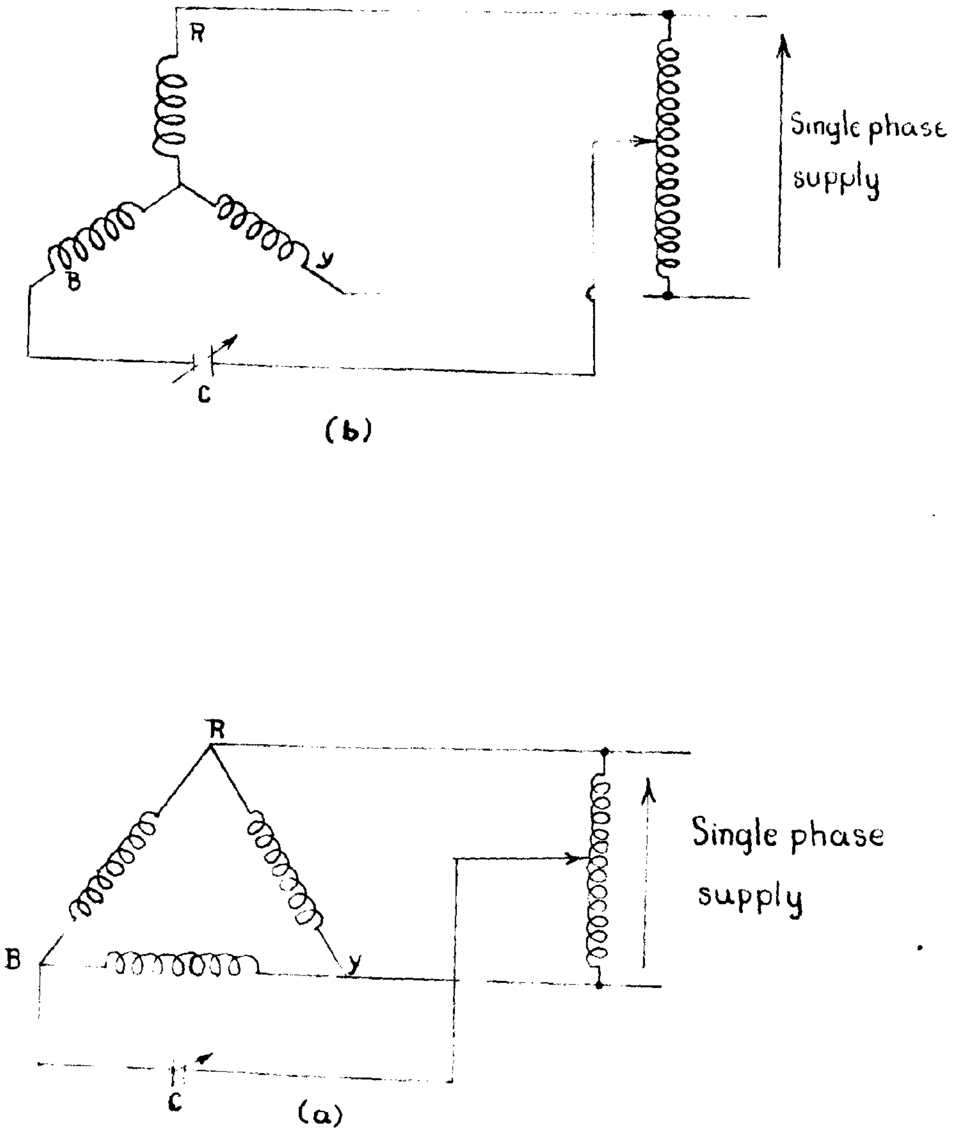


Fig 5.3(b)

out-put of the motor is limited mainly the current in c phase. The current through the capacitor decreases slightly as the load is increased indicating the capacitor volts and consequently the voltage across the b phase falls slightly as the load is increased.However, the extent of variations depends on the magnitude of the capacitor used. With 30 UF better results are obtained when the load is more than one third of full load.

Fig. 5-3. shows that the efficiency of the motor is slightly lower than that on balanced 3-phase circuits. Upto two third of full load the power factor is far better than that when operated on three phase circuits Fig.5.4a shows the forgue characteristics.The maximum forque occurs at low value of the slip and is about 60% of that on three phase circuits.Perhaps this may be the greatest limitation to the use of motor on single phase circuit.If the same capacitor is used at the start also the starting forque will be low. From the fig 5.4(b) it is observed that a much higher capacitor has to be used at the start.With suitable capacitor a starting forque greater than that available from 3-phase circuit may be obtained.

The drawbacks of running the motor on single phase supply are -(1) the rating of the motor will have to be reduced to 80% of its 3-phase rating,(2) The maximum forque is reduced, (3) in almost all cases the capacitance required at start will have to be greater than that required during running,(4) the motor gives balanced operation for particular load while at other loads unbalance would be large.



(b)

(a)

Fig 5 5

To achieve the balanced three phase condition Prof.R.K.Garg(26) in his paper " Operation of three Phase Induction Motors from single phase supply," suggests a phase conversion unit consisting of an auto-transformer and a variable capacitor, shown in fig. to enable operation of 3-phase induction motor on full performance and capacity from a single phase supply.By adjusting the capacitor and auto-transformer settings it is possible to obtain balance three phase operation at all loads in the normal working range of the induction motor.

Design improvements can be effected in the phase conversion unit to develop a compact unit consisting of an auto-transformer with a variable voltage range upto double the single phase supply voltage and capacitor 2-3 variable setting both conveniently operated by push button or remote control. A phase conversion unit may be incorporated into switching equipment and made available in standard sizes. However, the practical utility of this scheme will mainly depend on the development in the phase conversion unit. At present this system may be uneconomical because of high cost of phase-convertor unit.

5.3 ELECTRICAL EQUIPMENT FOR SINGLE PHASE EARTH RETURN SYSTEM:

The feasibility of single phase earth return system is not dependent upon non-standard equipment.The analysis of the scheme is based upon standard or easily obtainable equipment. To promote an understanding of some of the requirements of the equipment for the scheme a list of them is given below.

5.3.1 Transformers:

The transformers to be used for this system will be single phase. Of course, this is a simplification especially since one of the high tension windings will be solidly grounded. Secondaries should be suitable either for 220 volts or three wires 440 volts.The choice of the transmission voltage will be considerably influenced by the relative transformer costs to be expected for different primary voltages.If the single phase earth return lines were to be widely applied,the preparation of standard specifications would bewarranted and in that case the transformer would be designed with the correct ratio for earth return working and would have one high voltage bushing only.This should result in a cost lower than that of present single phase rural transformers assuming reasonable quantities are required.

5.32. Switch-gear and Relays:

The requirements of switch gear and relays are comparatively simple in case of this system. The cost for single pole switching would be approximately half that for three pole. In many switching along with cost reduction. One particular advantage here is the simplicity of use of fuses. In the single phase system,the circuit is cleared by operation of one fuse instead of the problem in polyphase circuit of the danger of motors running on one phase.Another advantage of the single wire system is that, greatly simplified air break switches mounted on non-conducting structure e.g. wooden poles, can open considerable amount of power with of course, no danger of arcing over between phases.

5.33 PHASE CONUERTER EQUIPMENT:

It is granted that single phase earth return system will require more expensive single phase motors.If the single phase earth return system were to be widely applied, the single phase motors required in the rural areas should be made available at reasonable cost.However, to meet the present conditions existing 3-phase motors can be used on single phase supply with the use of phase convertor equipment as discussed in 5.22. Information including costs, from equipment suppliers on all these methods will be much helpful.

Motor Starting Devices:

The extra capasitance needed during the starting of 3-phase motors on single phase supply may be secured by the use of electrolytic capacitor.It can be secured by the use of the capacitors rated at half the motor voltage but connected in series for running and connected in parallel during brief starting conditions. Suitable switching devices to change from start to run may be of different types. The simplest type would be simple enclosed double throw switch for the start and run positions.A mechanical switching device or an electrical relaying device to make a simple switch closer is an important alternative.Another most convenient design is to have centrifugally operated switch such as is in common use on single phase motors to switch from starting to running position In case of using this on a completed 3 phase motor,the centrifual switch would be mounted on the external shaft to accomplish the required purpose. Where 3-phase motor would be started by a star delta starter from a three phase line the same starter can be used equally well to start from the single phase source. Only small changes in internal winding would be required. The optimum capacitance for starting is little more when motor is in star than is required for running when in delta.

Whilst for most purposes,standard equipment will give good result with single phase supply, a thoroughly complete programme requires the full support of interested manufacturers of starters and switches.

5.4 ECONOMIC ASPECTS:

5.4.1 Line Conductor-

The areas of low load density resulting from small isolated loads , the line designs are governed by voltage drop limitation and not by the current carrying capacity of the conductor.The most economical line design will use the lowest cost standard conductors that is permissible on the basis of mechanical strength.This has normally meant the A.C.S.R. equivalent of 8 S.W.G. It may be expedient and economic to use a copper clad steel wire or even a galvanised steel wire.

5.4.2 Line Supports-

Line using single wire ground return should be exclusively carried on wooden poles.Metal supports are source of potential danger in this system as the metal supports will be at the same potential as the ground .Moreover, the wooden supports are cheaper than supports of steel or concrete Height of the pole required for single wire system may be reduced as it has to carry only one conductor.It is estimated that wooden supports cost roughly not more than 50 to 60 % of the cost of equivalent supports of steel or concrete.As the supports constitute about 20 to 25 % of the total cost of distribution lines,the reduction in initial cost will be substantial if treated wooden supports are used instead of other costlier supports . Experitments conducted by the Forest Research Institute at Dehradun, have shown that the poles of practically any Indian timber, if properly treated under pressure against white ants, borers and rots, can be expected to last 20 to 25 years.

5.4.3 Cost Comparison:

The cost of the single conductor line and of three phase line using the same operating voltage e.g. 11 Kv line to earth in case of single conductor line and 11 Kv line to line for 3 phase lines,can now be compared. On the single phase single conductor line the cost of the conductors, insulators, lighting arrestors, will be 1/3 of the cost for three phase line.Transformers would cost 20% less than the 3-phase transformers.Since the bulk of the cost of the three phase line, even for the small size conductor,is 1/3 of the cost,it can be seen that the single phase line will cost approximately 1/2 of the three phase line to carry the same power.

While the cost comparison between the single phase single wire transmission and three phase seems fairly obvious appendix II shows this comparison in detail . The results in the appendix II show that the cost of sub-station single phase single wire system is 79% of the cost of the 3-phase substation of the same capacity.The cost per mile of the single phase single wire line is only 46% of the three phase line for supplying the same power.

5.4.4 EXPERIENCE :

The single wire earth return system has been applied in New Zealand. The system is supplied originally from a three phase three wire 22 KV line and is isolated from the three phase system by an isolating transformer as is indicated in Fig. 1.1 The advantages claimed are :

1. Lower capital costs ACTUAL saving in H.V. line and substation are 25 - 30 % of the cost of comparable three phase line.
2. Lower material and labour costs due to simplified construction, permitting more rapid line construction.
3. Less interruption due to reduction of hazards caused due to simplified construction.
4. Reduced maintenance and operation costs.

The system has also been used in Canada and has been proved to be successful in reducing the cost of electrification.

CHAPTER - 6

CONCLUSION

CONCLUSION

It is technically feasible to use ground return for power lines, especially for rural distribution and this can bring about a considerable saving in the cost of the supply system.

The resistance and reactance of the earth return path have been found to be very small in comparison to that of the metallic conductor. Thus the earth can effectively replace a phase conductor as far as voltage regulation is concerned and it can rightly be taken as cost-free conductor with very little loss and the voltage drop.

One of the arguments against using earth as return path is the potential hazard due to build up of potential near the earth electrode. However, no hazards, not normal to the present systems, are introduced by this single phase system. On the contrary, because this system is evidently well adapted to wooden poles it would normally be much safer than the existing systems, and at the worst, fault conditions would not be different from than in a normal three phase system. The voltage gradients can be reduced by proper selection of the grounding system. The results of the field test and model tests show that a single driven rod gives rise to higher potential gradient and by employing either a triangular or square configuration potential gradients can be considerably reduced. The potential gradients can be kept sufficiently low by using the horizontal wires buried in the ground. It has been observed that the surface potential distribution near the electrode found out by the model and field test is nearly similar.

The induced voltage in the communication line running parallel to the single wire earth return line depends largely on the distance of separation between the two lines the length of parallel and current in the power line. By providing the sufficient distance between the two lines the voltage induced in the communication line can be kept within tolerable limits.

The chances of fault on such lines will be much less in comparison to other usual lines as there will be no chances of short circuit between the conductors or with cross arms. In case of high resistance earth fault proper protection can be provided by the scheme discussed in 4.2. This scheme was tested on the experimental single wire line for high resistance earth fault and was found to be working satisfactorily. The new static over voltage relay can be well used to prevent the potential hazard due to build up of potential near the current carrying electrodes.

The earth resistance measurement for different grounding arrangement show that the required low earth resistance can be obtained by using driven pipes in parallel. In the rockey soil it is advantageous to use horizontal wire burried to depth of 18" below the earth surface.

The use of the single phase system is handicapped due to non-availability of single phase motors required in the rural areas. If the single phase earth return system were to be widely applied the single phase motors required in these areas should be made available at resonable cost. It has been shown that the 3-phase induction motor on full performance and capacity from single phase supply, consisting of capacitor or combination of capacitor or reactor. A phase conversion unit may be incorporated into switching equipment and made available in standard sizes. However, the practical utility of this scheme will depend on the development in the pahse conversion unit. At present this scheme may be uneconomical because of high cost of phase conversion unit.

The feasibility of the single phase earth return system is not dependant upon non-standard equipment. As the system grows, there is no doubt that its special requirements will be met and that the equipment to meet these needs will become standard.

The cost comparison of the three phase system and the single phase earth return system shows that the cost of High voltage substation for single wire line is about 79 % of that for 3-phase High voltage substation and the cost of the single wire transmission line is only 46 % of the three phase line to carry the same power. The advantages of using this systems are :

Lower capital cost.

Lower material and labour cost

less interruption as there is only one conductor to fault.

Reduce maintenance and operation costs.

The greatest draw back of the system is that large motive loads for industries cannot be supplied by such system. This system is advantagious in those areas where immediate and future load demands are very small.

In view of the above investigations, the single phase earth return system warrants serious consideration to be adopted in India. The single phase earth return system should be thought of not as making a saving over the three phase but of making possible the supply of power in areas which otherwise could not be supplied at all. Thus this system is the proper means by which rural distribution can be extended in India so as to make the advantages of electricity available to all.

APPENDIX

APPENDIX I

IMPEDANCE OF EARTH RETURN PATH

According to ''Rudenbegg'', it is assumed that the line conductor can be taken as located along the axis of a semi-cylindrical trench of which the radius is the height of the conductor above the ground and that the earth has uniform resistivity.

It is also assumed that the current flow is uniformly parallel to the line, that is, the crowding of the lines of current flow due to finite earth electrode is neglected.

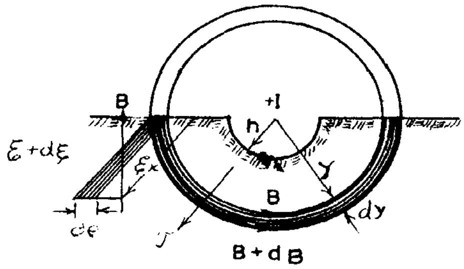


FIG 2

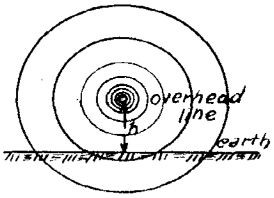


FIG 1

Fig. 1 shows an overhead line at the height h above the ground. Let us consider regions in the ground of some distance to the ground electrodes. We can substitute for the cross sectional diagram of Fig. 1 that of Fig. 2, wherein the current I of the conductor flows in the centre of a groove of semicircular shape and of radius h. For deriving the differential equations for the ground current, Fig. 2 shows two special magnetic lines of force. They would be concentric circles about the conductor if the ground uniformly surrounded the conductor in every direction. However, since the ground forms only semispace and the return currents flow only in this lower space, the lines of force are only approximately concentric circles about the current carrying conductor.

Let

- y - distance of any point from the line measured normal to the axis
- B - Magnetic flux density, the lines of which are presumed to be circles with the line as axis
- ϵ - Electric field strength
- μ - Permeability of the non magnetic material
- J - Current density at any point in the earth's surface
- ρ - Resistivity of the soil
- ~~μ — Permeability~~

All quantities are in M.K.S. Units.

Applying Ampere's law of magnetization

$$\oint B\,ds = 4\pi I \qquad \ldots\ldots (1)$$

to a toroid bounded by the cylinders y and y + dy we get

$$2\pi\,(y + dy)\,(B + dB) - 2\pi y B = \mu\, 4\pi J \times \pi\, y\, dy \qquad \ldots\ldots (2)$$

This yields the differential equation

$$\frac{1}{y}\,\frac{\partial}{\partial y}\,(yB) = \mu\, 2\pi\, J \qquad \ldots\ldots (3)$$

Further we apply Faraday's law of Induction

$$\oint \epsilon\, ds = -\,\frac{d\Phi}{dt} \qquad \ldots\ldots (4)$$

If this is applied to a longitudinal strip of length x as shown in Fig. 2, we have

$$x\,(\epsilon + d\epsilon) - x\epsilon = -\,x\, dy\,\frac{dB}{dt} \qquad \ldots\ldots (5)$$

This yields, as a relation between the electric and magnetic field strengths

$$\frac{\partial \mathcal{E}}{\partial y} = - \frac{\partial B}{\partial t} \qquad \ldots\ldots (6)$$

Finally, according to ohm's law, there is for every point in the ground

$$\mathcal{E} = \rho J \qquad \ldots\ldots (7)$$

By eliminating the magnetic and electric field strengths from Eqs. (3) and (7), we get the partial differential equation for the performance of the current density within the ground

$$\frac{1}{y} \frac{\partial}{\partial y} \left(y \frac{\partial J}{\partial y} \right) = - \frac{2\pi \mu}{\rho} \frac{\partial J}{\partial t} \qquad \ldots\ldots (8)$$

It is now assumed that the current density is sinusoidal with the same frequency as the current in the line.
Designating f (y) we thus make the statement

$$J = K \times f(y) \times e^{jwt} \qquad \ldots\ldots (9)$$

Where w denotes the angular frequency of the current and K a constant still to be determined. Substituting the value of J in Eq. (8) we get

$$\frac{1}{y} \frac{d}{dy} \left(y \frac{df(y)}{dy} \right) - j\, 2\pi \mu \frac{w}{\rho} f(y) = 0 \qquad \ldots\ldots (10)$$

This is a well known total differential equation, which is solved by any one of Bessel's function of the order zero. Since the current density must vanish at infinity, the complex Hankel cylinder function

$$f(y) = H_0 (\sqrt{j}\, ky) \qquad \ldots\ldots (11)$$

forms the solution. It is having complex argument in which

$$k = \sqrt{g\pi\mu \frac{w}{\rho}}$$
$$= 2\pi \sqrt{\frac{\mu f}{\rho}} \qquad \text{.....} \; (11a)$$

Now let us determine the constant of integration K of Eq.(9). Here we make use of the condition that the total current through the ground must be equal and apposite to the current in the conductor of amplitude I. Referring to Fig. 2, we have

$$\int_h^\infty J \pi y \, dy = \pi K e^{jwt} \int_h^\infty y H_o (\sqrt{j} \, k \, y) \, dy = -I e^{jwt} \; \text{...(1}$$

According to rule of integration for the Bessel function

$$\int x H_o (x) \, dx = x H_1 (x) \qquad \text{.....} \; (13)$$

where H_1 is the Bessel function of first order.

Thus we can write

$$\int_h^\infty y H_o (\sqrt{j} \, k \, y) = \left[\frac{y}{\sqrt{j} \, k} H_1 (\sqrt{j} \, k \, y) \right]_h^\infty$$

$$= - \frac{h}{\sqrt{j} \, k} H_1 (\sqrt{j} \, k \, h) \; \text{.......} (14)$$

and the constant of integration derived from Eq. (12) is

$$K = \frac{\sqrt{j} \, k}{\pi \, h \, H_1 (\sqrt{j} \, k \, h)} I \qquad \text{.....} \; (14)$$

Therefore, the current density in the ground is for any distance y

$$J = \frac{\sqrt{j} \, k}{\pi \, h} \frac{H_o (\sqrt{j} \, k \, y)}{H_1 (\sqrt{j} \, k \, h)} I e^{jwt} \qquad \text{....} (15)$$

For the functions H_0 and H_1 there exists tables and curves (27) so that they can be used in calculations with the same ease as, for example, trignometric functions.

For all frequencies used in power transmission, with the value of kh upto 0.5 we can make the following approximation

$$H_1 (\sqrt{j}\ k\ y) = \frac{-2\sqrt{j}}{\pi\ k\ y} \qquad \ldots\ldots\ldots (16)$$

Therefore the constant of integration of Eq. (14) is with $y = h$

$$K = - \frac{K^2}{2} I \qquad \ldots\ldots\ldots (17)$$

and the current density is by Eq. (15)

$$J = - \frac{k^2}{2} H_0 (\sqrt{j}\ k\ y) \times I\ e^{jwt} \quad \ldots.(18)$$

From the nature of H_0 and the above equation it can be seen that the current density goes on decreasing as the distance from the line increases. For larger distances the current density decreases rapidly and for about $k\ y = 3$ H_0 attains such a value that no substantial current density is left. For numerical calculations we may use an asymptotic approximation for the function H_0 with small arguments upto $k\ y = 0.5$ this is

$$H_0 (\sqrt{j}\ k\ y) \quad \left[\frac{1}{2} - j\ \frac{2}{\pi} \log \frac{2}{k\ h} \right] \qquad \ldots\ldots (19)$$

Where = Bessel's constant = 1.781

The voltage over length x is then given by

$$e = \rho \times J \qquad \ldots\ldots (20)$$

If we replace first the current density by Eq. (18) and then k^2 by Eq. (11a) the resistivity cancels. This yields

$$E = - \mu x \, w \, I \, x \, \pi \, H_0 \, (\sqrt{j} \, k \, y) \, e^{jwt} \quad ..... \ (21)$$

Using the approximation (19) the amplitude of the alternating voltage at the earth's surface directly under the conductor i.e. $y = h$

$$E = - \mu x \, w \, I \left[\frac{\pi}{2} - j \, 2 \log \frac{2}{k \, h} \right] \quad .... \ (22)$$

This represents the voltage drop of the total alternating current $-I$ in the ground over a distance x. This expression is similar to that of voltage in circuit containing resistance R and self inductance L

$$E = - I \, (R + jwL)$$

By comparison, we get the effective resistance of the return currents as

$$R = \frac{\pi}{2} \mu \, w \, x$$

$$= \pi^2 \, f \, x \quad 10^{-7} \text{ ohm/meter}$$

The value $\mu = 10^{-7}$ is the permeability of non magnetic material in the meter-kologram second system.

Similarly, the self inductance

$$L = 2x \log_e \left(\frac{0.178}{h} \sqrt{\frac{10^7 \rho}{f}} \right) 10^{-7} \text{ Henries/meter}$$

APPENDIX II

TABLE I

Unit Cost of 11 KV 3-Phase Transmission Line on Wood Poles with an average span of 300 ft.

Unit = 1 Mile

S.No.	Material	Quantity	Rate Rs.nP.	Cost Rs.nP.
1)	**Supports**			
	(a) Wooden Poles 30' high	18 nos.	60.00	1080.00
2)	**Conductors**			
	(a) ACSR conductor equivalent to 0.025 sq.in. copper area.			1400.00
	(b) Earth wire 7/16 G.I. conductor.	450 lbs.	0.90	405.00
3)	**Brackets**			
	(a) 4'-0'' centre straight cross arm bracket 3'' x $1\frac{1}{2}''$ x $\frac{1''}{4}$ channel with stirrups.	16 nos.	20	320.00
	(b) 8'-0'' centre double pole channel cross arm double pole.	2 nos.	30	60.00
	(c) Top Insulator brackets	16 nos.	4.00	64.00
	(d) Earth wire brackets	17 nos.	4.00	68.00
	(e) Cross bracings	1 no.	30.00	30.00

S.No.	Material	Quantity	Rate Rs.nP.	Cost Rs.nP.
4)	Insulators			
	(a) 11 kV pin insulators	51 nos.	10.00	510.00
	(b) 11 kV disc insulators	6 nos.	25.00	150.00
5)	Miscellaneous			
	(a) 3/8''x 6' stay rods complete with anchor plate, bow, thimbles etc.	12 nos.	25.00	300.00
	(b) Stay clamps	12 nos.	5.00	60.00
	(c) Bolts and nuts		L.S.	50.00
	(d) Earthing	4 nos.		150.00
	(e) Painting of iron parts		L.S.	300.00
	(f) Labour and transpot		L.S.	400.00
	(g) Supervision 15 p.c. on labour charges.			60.00
				5407-00
	(h) Contingency	5 p.c. on total		260.35
				5667.35

TABLE II

Unit cost of 11000/400/230 Volts Pole- Mounted Substation

Capacity 25 KVA, 3Phase

S.No.	Material	Quantity	Rate	Cost.
1.	11 kV AB Switch	1 No.	500.00	500.00
2.	11 kV horngap fuse	1 set	150.00	150.00
3.	Earthing	3 nos.	50.00	150.00
4.	Transformer D.P.Structure	1 No.	L.S.	250.00
5.	Brackets for L.T. Line		L.S.	50.00
6.	H.T.and L.T. Jumpers		L.S.	30.00
7.	L.T. wiring from transformer to outgoing L.T. Mains as under :-			
	(a) 100 amp I.C.T.P.switch	1 No.	200.00	200.00
	(b) G.I.Pipes and bends		L.S.	100.00
	(c) V.I.R. Wires		L.S.	250.00
	(d) Sockets and soldering		L.S.	30.00
8.	25 kVA 3-Phase 11 kV/400/230 volts 50 c/s outdoor type transformer.	1 No.	2900.00	2900.00
9.	Labour and transport			300.00
10.	Supervision 15 p.c. on labour			45.00
				5055.00
11.	Contingency 5 p.c. on total.			252.75
				5307.75

TABLE III

Unit Cost of 11 KV 1-Phase Single wire earth return transmission line on wooden poles with an average span of 300 ft.

....

Unit = 1 Mile.

S.No.	Material	Quantity.	Rate	Cost
1.	Supports			
	(a) Wooden Poles 30' high	18 Nos.	60.00	1080.00
2.	Conductors			
	A.C.S.R. Conductor equivalant to 0.024 sq.in copper area.			466.00
3.	Brackets			
	Insulator brackets		L.S.	80.00
4.	Insulators			
	(a) 11 kV pin insulators	16 nos.	10.00	160.00
	(b) 11 kV disc insulators	2 Nos.	25.00	50.00
	Miscellaneous			
	(a) Stay rods complete with anchor plate, bow, thimbles, etc.	12 Nos.	20.00	240.00
	(b) Stay clamps	12 Nos.	3.00	36.00
	(c) Bolts and nuts etc.		L.S.	30.00
	(d) Earthing		L.S.	100.00
	(e) Labour and transport		L.S.	200.00
	Supervision 15 p.c. on labour and transport			30.00
				2472.00
	Contingency 5 p.c. on total			123.60
				2595.60

TABLE IV

Unit Cost of 11 KV/440/220 volts pole mounted substation capacity 25 KVA, single phase

S.No.	Material	Quantity	Rate Rs.nP.	Cost. Rs.nP.
1.	Single phase 11 kV switch	1 no.	200.00 (approx)	200.00
2.	Single phase 11 kV horngap fuse.	1 no.	40.00 (approx)	40.00
3.	Earthing			200.00
4.	Transformer D.P. structure		L.S.	300.00
5.	H.T. and L.T. Jumpers		L.S.	15.00
6.	L.T. wiring from transformer to outgoing L.T. mains.		L.S.	350.00
7.	25 KVA single phase 11000/440/220 volts 50 c/s out door type transformer.	1 no.	2600.00	2600.00
8.	Labour and transport.		L.S.	200.00
9.	Supervision 15 p.c. on labour			30.00
				3935.00
10.	Contingency 5 p.c. on total			196.00
				4131.00

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