SYSTEMATIC DESIGN OF ECONOMIC EARTHING MATS

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by
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1966

CERTIFICATE.

Certified that the dissertation entitled 'SYSTEMATIC DESIGN OF ECONOMIC EARTHING MATS' which is being submitted by Sri Madanjit Singh, in partial fulfilment for the award of the degree of Master of Engineering in Electrical Power Systems of University of Roorkee, is a record of candidate'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 to certify that he has worked for a period of 13 months from June 65 to Aug. 66 for preparing dissertation for Master of Engineering Degree at the University.

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Roorkee,
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INTRODUCTION

With the expansion of power systems, the increasing maximum ground fault current results in dangerous potential rise of grounding systems. The hazard can be avoided only by the control of local potentials i.e. by grounding mats. Reliability of electric system is the requirement for its good operation, and safety to human beings and equipment is the criteria for its design. Revisions in the design are being demanded keeping in view the former factor for life of the grid and later for safety. But the ever rising cost of material due to limited resources with tight import policy and long life of grid, calls for attention from economic point of view.

The general consideration for grounding systems throws light on the subject. There are a number of factors to be considered for a safe and economic design. As the resistivity of soil is one of the main factors in computing the grounding resistance, the potential gradients, corrosion and protection of grid, its study forms an important part. This is the factor which affects the total conductor length and depth of burial and thus directly affects the cost.

To find the total potential rise, the resistance of grid is the next factor to be studied which requires the knowledge of various methods of computing the grounding resistance of various type of electrodes either by theoretical derivation or by emperical formulae. The non-homogeneity of soil makes the problem more difficult and thus requiring more extensive study.

Human safety wants the study of electric current on human beings i.e. magnitude and duration of electric current and its effect, the electric shock. This helps in fixing the tolerable potentials inside and outside the grid and thus the size of mesh. Due to non-homogeneous soils, special attention is required to obtain tolerable potential gradients.

The choice of material plays an important role in determining the size of conductor, the corrosion and type of protection and finally the cost. It depends on soil properties from corrosion point of view and thus requires a study of corrosion phenomena and its protection. The cost comparison gives a clearer picture about the choice.

The co-relation of above factors gives the means for safe design, the choice of material and its best utility, the economy. The demanded long life of grid increases the total cost, because of expensive protection against corrosion, again challenges the economy and the choice of material. The correct estimate of the magnitude of fault current solves the problem further.

To deal adequately with the problem, the present report is divided into the following chapters:

(1) General considerations for grounding systems.

(2) Resistivity of soil.

(3) Computation of grounding resistance.

(4) Study of electric shock and safety to human beings.

(5) Grid material, corrosion and its protection.

(6) Design criteria of grounding grids with economic considerations.

(7) Examples of practical design for homogeneous and non-homogeneous soils.

CHAPTER - 1

GENERAL CONSIDERATIONS IN GROUNDING

1.1. GENERAL:

Due to the industrialization of the country, large amounts of electric power are required to be generated and transmitted, which necessitate the use of high voltages. Due to the higher voltages and power, arises the problem of large substations capable of efficient and safe operation. Reliability of supply, safety to equipment and personnel becomes an important problem, which led to the rapid progress in the earthing arrangements. The earthing of an electric installation plays an important part as regards the behaviour of the network and personnel safety when the fault occurs. So, great care is required while designing the earthing arrangement.

The earthing problems are of complex nature due to a number of reasons. The earth is a poor conductor. It is not homogeneous and has characteristics of which very little knowledge is available. The conductors and electrodes buried in soil are out of sight and often have a complicated shape and it is difficult to examine them. The probability of contact in case of personnel safety is difficult to formulate mathematically. Finally the poor ground conditions give financial difficulties for installing a good earthing system. Due to these difficulties this field was not developed fully and empirical methods were employed, but now the designs are based more on mathematical approach and they are more scientific and accurate; moreover studies are being made to go deep into the economic aspect.

CTION AND CLASSIFICATION OF EARTHS:

he purposes of earthing electric installations are
on of installation, improvement in quality of service
ty of personnel. The former aim is achieved by facili-
he drainage of lightning discharges and ensuring optimum
nce of protective devices when faults occur and the
y reducing the step and touch voltages occuring under
r fault conditions to safe values.

he grounds can be broadly classified as 'system' ground
ty'ground. The system ground forms the integral part of
ork and forms links, permanent or temporary between the
and ground, either directly or through suitable impedanc
depends the behaviour of network in case of earth fault
lant or on the line.

TRAL GROUNDING:

enerally the neutral is effectively grounded in case of
tworks above 33KV because of the following advantages[1]:-

(i) The fundamental frequency voltage is well controlled.

ii) The duty of circuit breakers when interrupting double line to ground fault is eased.

ii) Arcing grounds can not occur.

iv) Ground fault relaying is fairly simple.

(v) The voltage rating of a given design of lightning arrester can be increased by about 25 percent.

The following are the disadvantages:

(i) Every ground fault is converted into a short circuit and faulty section of the line must be disconnected, thus causing interruption of supply.

(ii) The line outages may create stability problem.

(iii) Heavy ground fault currents are likely to cause considerable damage at the fault point and the dynamic stresses created extend over large parts of the system.

(iv) The danger to human beings and live stock is increased due to large fault current if they happen to be in the proximity of the fault.

The adverse effects due to (i), (ii) and (iii) are minimized by duplicating supply, cutting down the fault clearing time and applying high speed reclosure. Whereas to minimize the effect due to '(iv)' the earthing system is to be carefully designed as the voltage rise at the place of fault depends upon the resistance to ground.

1.4. INSULATED NEUTRAL OR WITH PETERSON COILS:

In case of h.v. networks having sufficiently short length and insulated neutral or with Petersen coils the following are the advantages:

(i) Performance of the plant is good by limiting earth fault currents to low values, so that the thermal and electrodynamic effects are less pronounced.

(ii) This low fault current is of help in ensuring reliable service and in favouring self extinction of arcs to earth.

(iii) It also reduces the discharge voltage of these arcs through the protective earth and thus contributes to the human safety. On the other hand following are the disadvantages.

(i) A network with insulated neutral or with quenching coils induces relatively high dielectric stresses in the plant.

(ii) The discharge to earth continues over a considerable period and this may give rise to a serious risk of accident when the protective earths or contacts taking their place have a certain resistance.

1.5. SYSTEM AND SAFETY GROUND:

As the system ground is integral part of the network so its basic purpose is the protection of system and improvement in the quality of service. The system ground also ensures, to a certain extent, the safety of personnel because of high speed fault clearing.

The 'safety ground' is not connected to the conductors of the network, but to the objects which risk accidental contact with the conductors and which would be dangerous if maintained at a high potential over a period. By connecting the non-current carrying parts of equipment to a low resistance, a sufficiently high current is allowed to flow in the case of conductor touching the frame to ensure high speed isolation of the equipment. This ensures to a great extent safety against touch voltage. Thus the basic purpose of safety ground is the protection of personnel.

Safety ground cannot always limit the voltages at the fault to safe values, especially on h.v. networks with earthed neutral. Human safety is thus almost exclusively ensured on these networks by high speed circuit breaking, which reduces to an infinitesimal value the chances of a person finding himself on the spot where a fault occurs at the precise instant and in a hazardous attitude. The object of safety ground is simply to allow the passage of a sufficienty high current to ensure high-speed protection. Accidents to people are practically non-existent on h.v. networks with earthed neutral and suitable protection. They are certainly much rarer than on networks with insulated neutral.[2]

It is some-times suggested that separate systemand safety grounds will avoid the danger arising due to potential gradients. When the system ground is situated in an inaccessible spot, the ground fault current does not flow through safety ground and hence hazard due to potential gradients are avoided. This is only the case when fault occurs outside the station. Although majority of ground faults occur outside the station, but it creates a hazard, when fault is inside, due to heavy current flow from safety ground to system ground. So this is not avoiding hazard. But in case of inter-connected system, a met~~t~~alic path is offered to part of current which completes the circuit through local neutral. The magnitude of fault current is also greater in case of separate safety and system grounds.[2] The resistance of grounding system is greater in case of separate system and safety ground than inter-connected ground, which means a smaller current flow that may not operate protective gear and fault remains uncleared. Thus creating a hazard. The installation of a separate system ground requires a tremendous amount of land outside the station. Also for effective separation of two grounds, a large distance is required, which means a long insulated neutral is required and thus creating a problem.

Finally the cost of two separate grounds will be quite high as compared to inter-connected ground itself.

CHAPTER - 2

CHARACTERISTICS OF SOIL

Soil has been used as a conductor of electricity since early days of electric supply. It was deliberately used as a return conductor in some cases, but it is very seldom adopted now-a-days since the earth has many failings as a conductor. It was thought for some time that, because the dimensions of any current path through the earth would be very large, the resistance of any such path would be negligible, but it is not so. The main use of earth is connected with safety as far as the electric supply industry is concerned.

The electric properties of soil are of interest and importance, particularly, the specific resistance. The resistivity is one of the factors in determining the resistance of any earth electrode. The studies of resistivity and the manner in which it varies can give useful information as to the nature of sub-soil.

Most of the soils and rocks when dry are non-conductors of electricity, because the main constituents are silicon dioxide and aluminium oxide which are good insulators. The conductivity of soil is due mostly to salts and moisture embeded between these insulators.

The main factors which determine the resistivity of soil are:-

(a) Type of soil

(b) Chemical compositions of dissolved salts.

(c) Concentration of the salts dissolved in contained water.

(d) Moisture content.

(e) Temperature

(f) Grain size of material and distribution of grain size.

(g) Geological age of strata.

(h) Sub-soil water level.

2.1. TYPE OF SOIL:

In determination of resistivity of soil, type of soil is very important. It is difficult to define clearly the type of soil, because each type can cover variety of soils and same general type of soil in various localities may have different resistivities.

The table giving typical values of resistivity of some soils[3] is as under:

Type of soil	Resistivity in ohm-cm.
Loams, garden soils etc.	500 - 5000
clays ..	800 - 5000
Clay, sand & gravel mixtures.	4000 - 25,000
Sand & gravel ..	6000 - 10,000
Slates, shale, sandstone etc.	1000 - 50,000
Crystalline Rocks ..	20,000 - 1,000,000

These figures have been collected from a number of sources, but can only be taken as an approximation as to the order of resistivity to be expected.

2.2. EFFECT OF MOISTURE CONTENT AND OF DISSOLVED SALTS IN WATER:

The quantity of water and the nature and amount of dissolve salts play an important part in determining the resistivity. The actual amount of water is dependent on a number of factors and

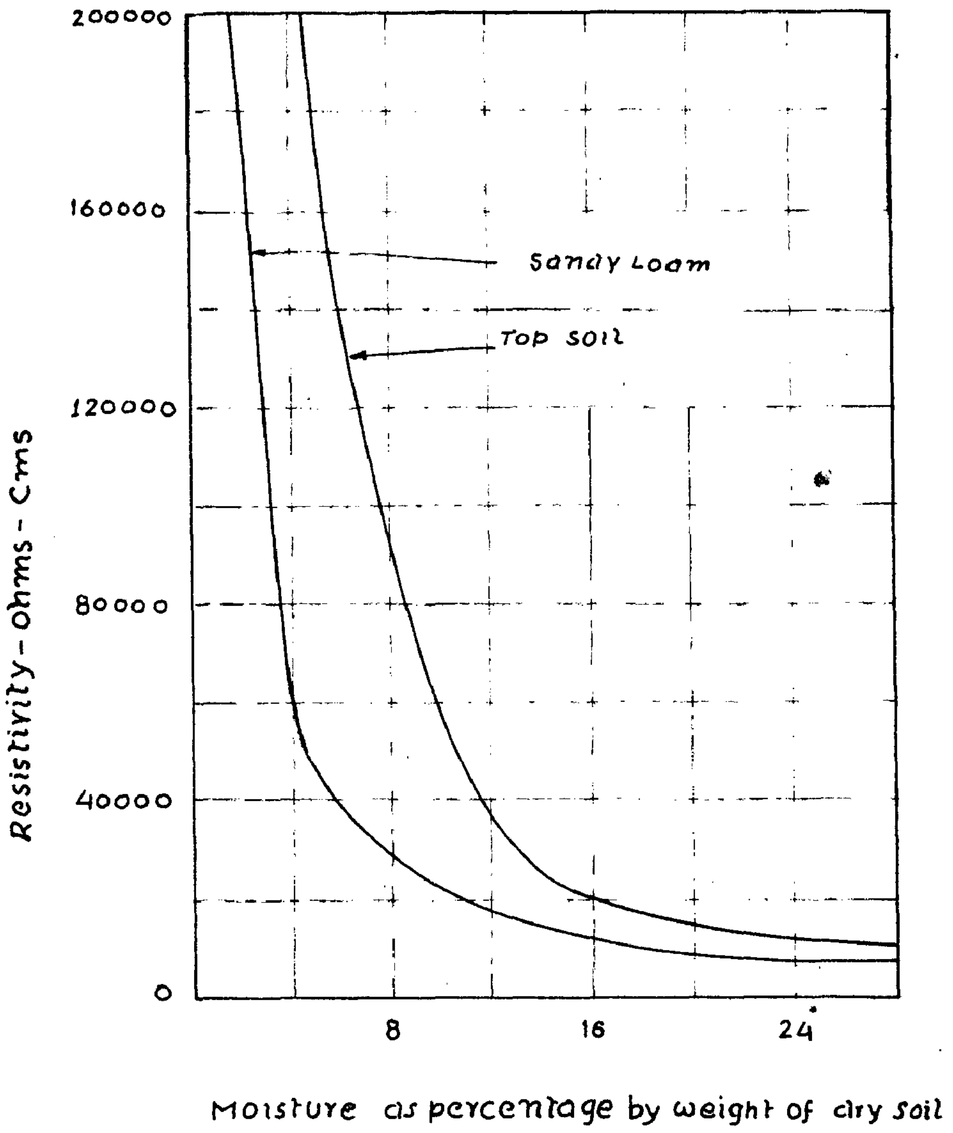

FIG 2.1 VARIATION IN SOIL RESISTIVITY WITH MOISTURE CONTENT

is likely to be a variable quantity. It will vary with the weather, the time of year, the nature of sub-soil and the depth of permanent water table. The soils are very rarely really dry and these occur very often with moisture content more than 40%.

Higgs used two kinds of soils, top soil and sandy loam. The manner in which the resistivity of these soils varies with moisture content is illustrated in fig.2.1.The resistivity falls rapidly till the moisture content is 14-18%, but beyond this the rate of decrease is much less. Moisture content is likely to increase with increasing depth in most localities, but it is not necessary that due to a lot of moisture, the resistivity is necessarily low.

2.3. EFFECT OF DISSOLVED SALTS IN WATER:

As the resistivity of water is dependent on the amount of salts dissolved and resistivity of soil depends on the amount of water, so the resistivity of soil will depend on the amount of the salt dissolved in water. Fig. 2.2 give the curves[3] showing quite clearly that quite a small quantity of salt dissolved can reduce resistivity very considerably from infinite value of really pure water. It will also be noted that different salts have different effects and this is probably part of explanation why resistivities of similar soils from different localities vary considerably.

2.4. EFFECT OF GRAIN SIZE AND ITS DISTRIBUTION:

In the determination of resistivity, grain size plays an important part. The grain size and its distribution undoubtedly has an effect on the manner in which the moisture is held. With large grains, moisture is probably held by surfacetension at

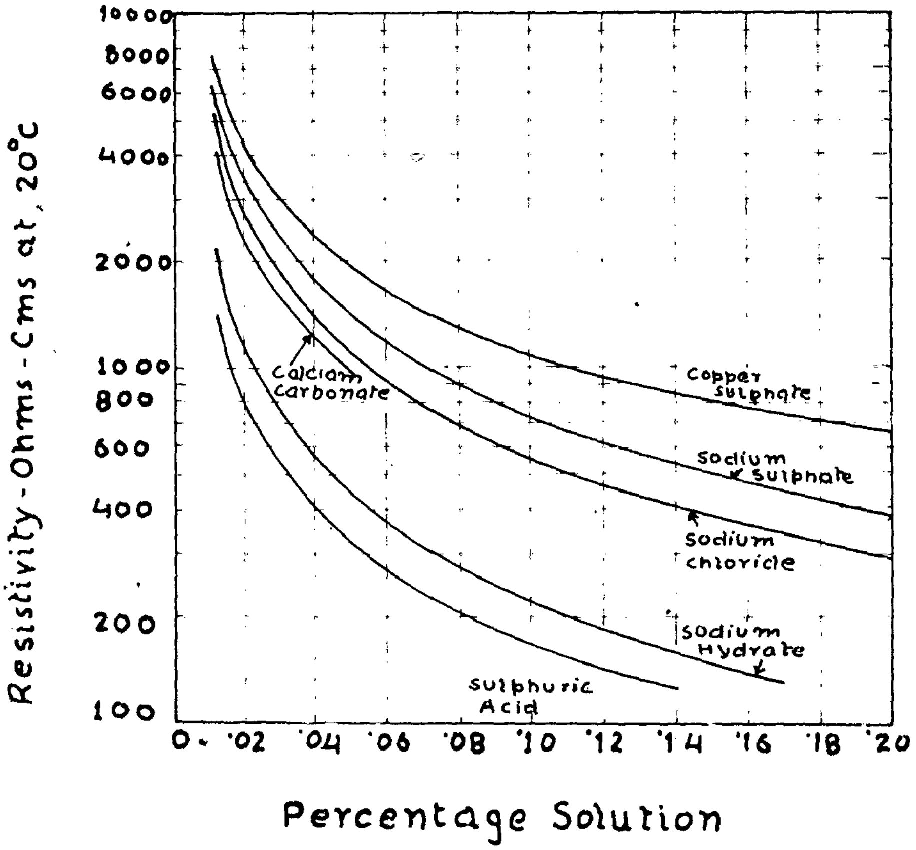

FIG 2.2 TYPICAL RESISTIVITY CURVES OF SOLUTIONS

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points of contact with the grains. If, however, grains of various sizes are present, spaces between large grains may be filled by smaller ones and resulting in reduction in resistivity. In order to have some idea of volume of free space which can be filled with water, it is assumed that grains are of spherical shape. The most compact arrangement of these is obtained when the lines joining, the centres of spheres form an equilateral parallelopiped having face angle 60° and 120°. For such an arrangement the pore volume amounts to 25.95 percent of total and is independent of grain size. The igneous rock gives this volume 0.2 to 2%, ordinary clay and sand 8 to 15 percent, and for porous conglomerates and cellular limestone, it is 25 percent[3].

2.5. EFFECT OF TEMPERATURE:

The resistivity of soils rises abruptly when the temperature falls below 32°F. For increasing temperatures above 32°F, the resistivity will decrease. However, in unusual cases of prolonged heavy current, the boiling point of water may be reached in the vicinity of an electrode, so that drying of soil and high resistivity may result[5].

As soil structures varies from place to place and also with depth large variations in value of resistivity may occur. Thus knowledge of the soil resistivity values at the substation site, is necessary for developing an economic and safe design of the grounding system. The knowledge of soil resistivity can be had from resistivity measurements.

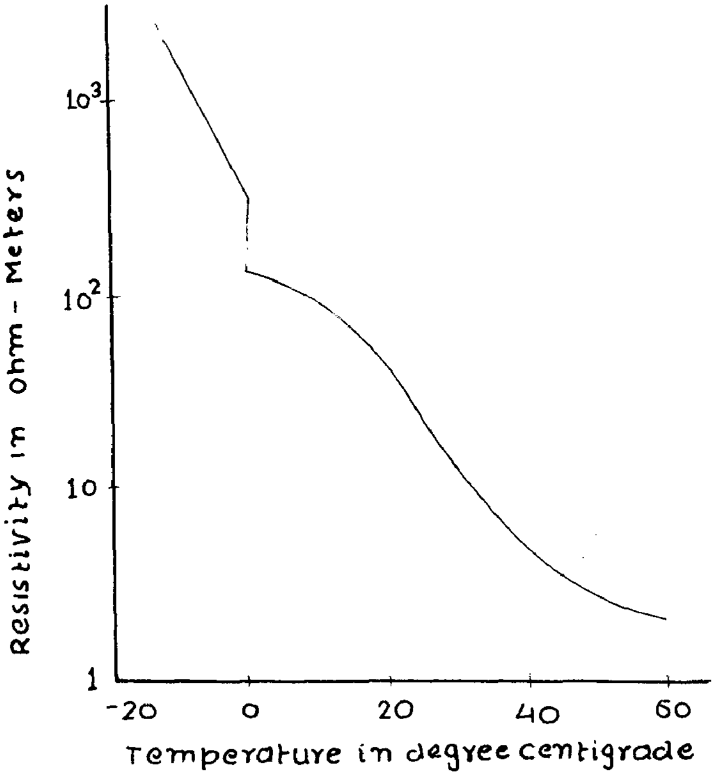

FIG 2.3 VARIATION OF RESISTIVITY WITH TEMPERATURE

2.6. SOIL RESISTIVITY MEASUREMENTS:

The estimates based on the classification of soil will permit only a crude approximation of resistivity. Electrical resistivity tests are therefore very desirable. These should preferably be made at a number of places within the site, and with different probe spacings, to get an indication of any important variations of resistivity with location or depth. The number of such readings taken will normally be greater where these variations are large; especially if some resistivity readings are so high as to suggest a serious safety problem.

Where resistivity varies appreciably with depth, it is often desirable to use a range of probe-spacings sufficient so that a fairly accurate method for still greater spacing can be found by extra polation.

The method of measurement in general used is based on equation 2.1 below described by Dr. F. Wenner of U.S. Bureau of Standards. Two current electrodes and two intermediate potential electrodes, each of small dimensions are placed in the earth at equal distances apart in a straight line to depth B. The voltage between two potential electrodes is then measured and divided by the current between the two current electrodes to give a value of mutual resistance 'R'.

Then-

[illegible]

$$P = \frac{4\pi AR}{1+\frac{2A}{\sqrt{A^2+4B^2}} - \frac{2A}{\sqrt{4A^2+4B^2}}} \quad .. \quad (2.1)$$

where P is the resistivity of soil in ohm-meters.

R is the resistance in ohms resulting from dividing the voltage between potential probes by the current flowing between

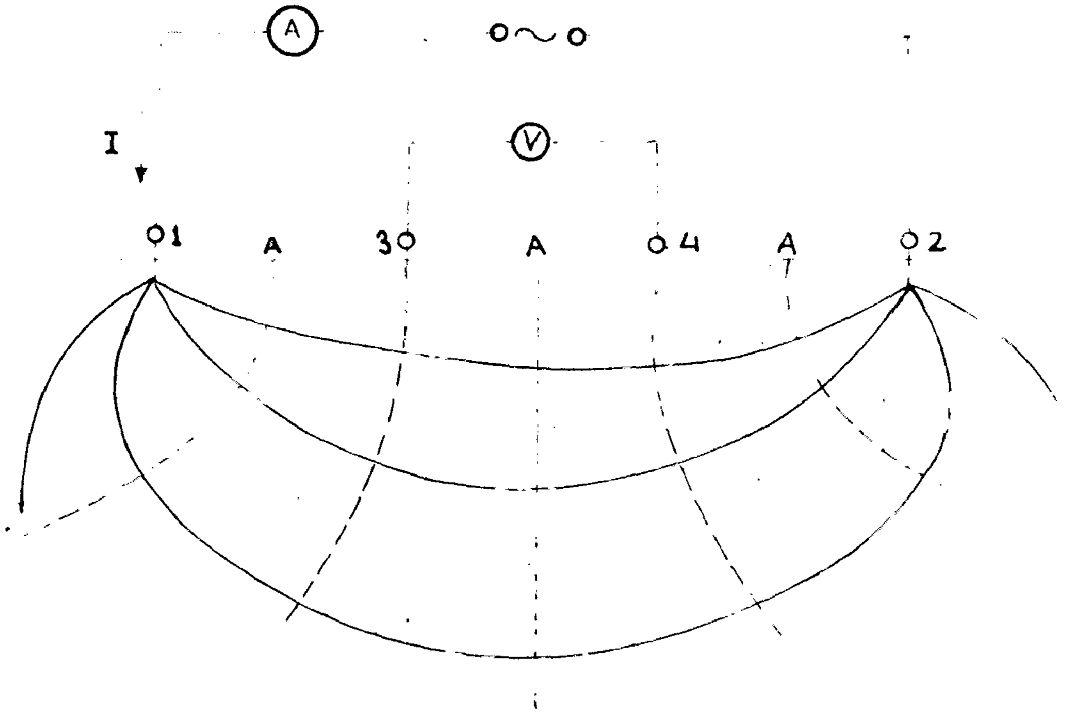

FIG 2.4 MEASUREMENT OF RESISTIVITY WITH FOUR ELECTRODE METHOD

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the current electrodes.

A is the distance between adjacent electrodes in meters.

B is depth of electrodes in meters.

If 'B' is small compared to 'A', as in the case of probe penetrating the ground a short distance only. The above equation can be simplified as follows.

$$P = 2\pi AR. \qquad \ldots \qquad \ldots \quad (2.2)$$

The derivation of the above equation is based on the assumption that the soil resistivity is uniform. When the apparent resistivity measured with above method varies with probe spacing, it indicates that the resistivity varies with depth.

The short coming of the above method is that the magnitude of potential decreases rapidly between the two inner probes, when probe spacing is increased to relatively large values. This has often resulted in inadequate sensitivity with the usual measuring devices.

Readings with wide probe spacings are required, when resistivity at greater depth is desired. Sensitivity can be improved in such cases by increasing the spacing between the potential probes, bringing each of these nearer the corresponding current probe. The simplified equation of Wenner is then no longer valid; however, the resistivity[6] can be computed as follows:

$$P = \frac{\pi(1 - \ell^2)}{2\ell}\, aR \qquad \ldots \qquad \ldots \quad (2.3)$$

where-

P = resistivity in ohm-ft.

a = one half distance between current probes in feet.

α = distance between potential electrodes divided by distance between current electrodes.

R = Reading of instrument in ohms.

2.7. EVALUATION OF SOIL RESISTIVITY TESTS:

In order to obtain information regarding the vertical and horizontal variations in soil resistivity over the site selected for the substation, resistivity curves are very helpful. A resistivity curve is a graph with probe spacing as abscissa and resistivity as ordinate.

2.7.1. Soil uniformity:

The 'penetration' of test current i.e. the distance from the surface to the deepest point reach by an arbitrarily defined large portion, say 70% of the total current is directly related to probe spacing. The layers which have an influence on the ground resistance value of a station extend down to a depth of the order of equivalent radius of the station (the radius of circle having same area as the station's grounding network).

Thus to investigate uniformity or otherwise, of soil at a given site, the resistivity tests have to be repeated with probe spacings upto equivalent radius of the station. Generally a number of measurements are taken with probe spacings increasing from 2 to 60 meters, in 5 to 15 meter steps. With the help of these measurements the resistivity curve is plotted. A number of such curves are plotted for a number of locations over the site of substation. From these curves an average curve is deduced. If the resistivity variations are within 20 to 30 percent,[7] the soil under consideration can be taken as uniform. A suitable value of resistivity is taken for design purposes after analysing the resistivity curve, in case the variation is more than as mentioned above.

2.7.2. Non-Homogeneous Soil:

Soil is nearly always non-homogeneous and these non-homogeneties can take many forms. In most cases there are several layers of soil which may be loam, sand, gravel, clay or mixtures of these, and rocks. These layers may be approximated horizontal and parallel to the surface. The water table acts as an additional layer, since the increase in moisture content below the water table will result in a significant change in resistivity in a number of instances. Because the lateral changes in the resistivity of the soil are usually small and gradual compared with vertical ones, the soil resistivity only is considered as a function of depth below the surface for analysis.

The resistivity of non-uniform soil may be represented by the resistivity curve (the relation between the measured resistivity using 4 probe method and the spacing of probes). Analytically it may be approximated by[9]

$$P = P_2 - (P_2 - P_1)e^{-bs}\,(2-e^{-bs}) \qquad \text{.. (2.4)}$$

where P is the measured resistivity with probe spacing s. P_1, P_2 and b describe the prevailing parameters of non-uniformity of soil. The values of P_1 and P_2 are determined from the resistivity curve. 'b' is calculated from the equation above, so that it satisfies the required curve. In order to determine P_a, the following is the method based on the chart-

Select the area on the left ordinate and follow along a

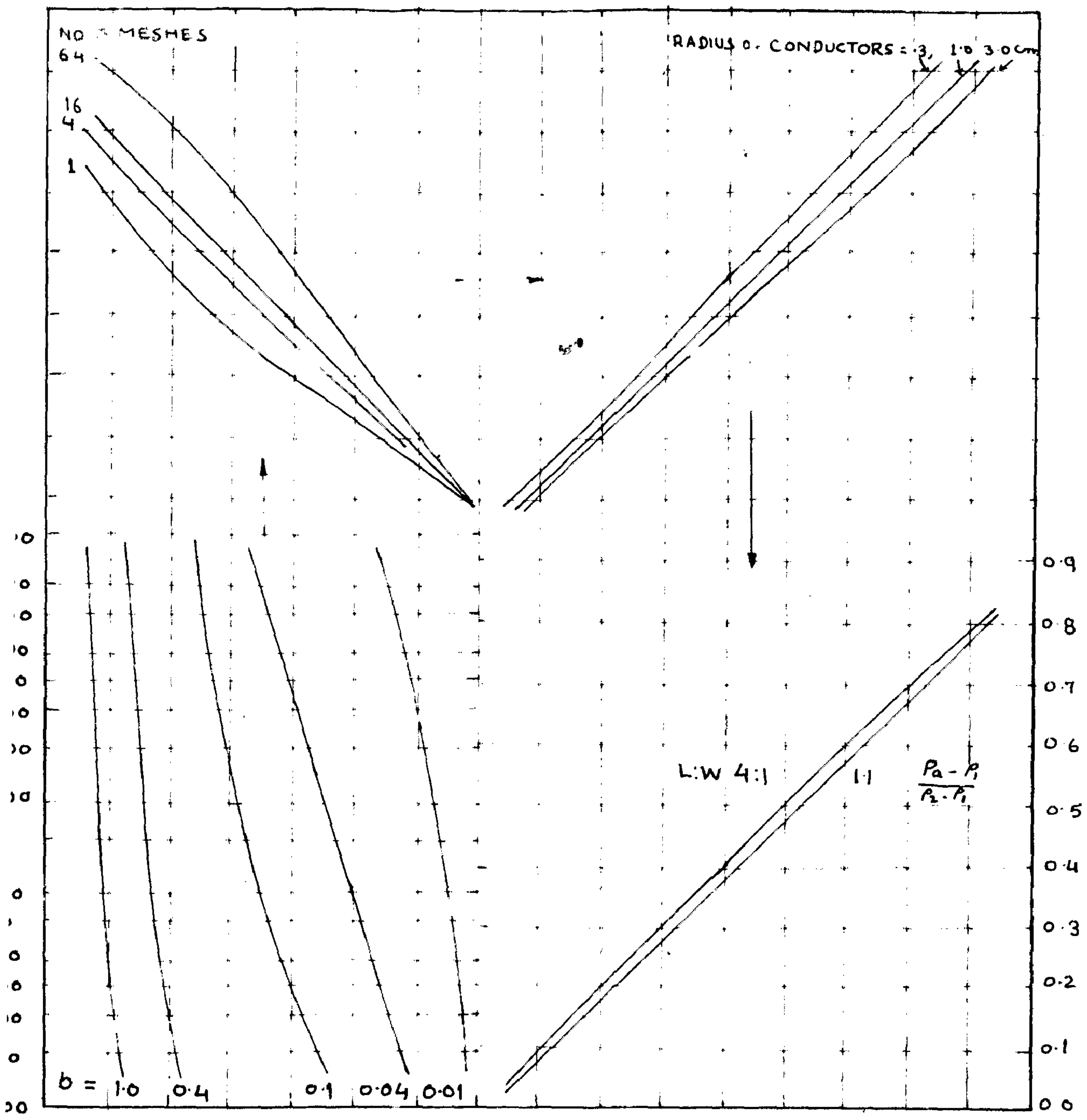


FIG 2.5 APPARENT RESISTIVITY FOR RECTANGULAR GROUNDING GRIDS.

horizontal line, where it intersects for the required value of 'b'. Then proceed vertically upward to the intersection with the curve representing the number of meshes, continue horizontally to the right until the curve representing the radius of conductor is reached. From this point follow vertically down to the intersection on the required line of L/W (length to width), then proceed horizontally to the right ordinate axis and read the ratio $\frac{P_a - P_1}{P_2 - P_1}$, from which P_a is easily evaluated by substituting the values of P_2 and P_1.

In order to cover the area adequately at the station site resistivity measurements should be taken at several positions. The probe spacing may be started at 2 meters and increased in convenient steps to a large probe spacing where the earth resistivity curve becomes almost flat. These tests should be conducted repeatedly over a long period of time, since the resistivity will vary with season. It is worthwhile to extend the test at least one year. Thus apparent resistivity depends not only on the soil conditions but also on the size of grid. The geometrical configuration of the grid and number of meshes beyond 64 gives practically no reduction in the apparent resistivity.

CHAPTER - 3

COMPUTATION OF GROUNDING RESISTANCE

3.1. GENERAL:

In the design of grounding systems, it is one of the most important steps to compute the resistance to ground of the system. The term 'resistance to ground' means the resistance between the electrode system and another electrode in the ground at infinite spacing. In determining the resistance the well known analogy is used, which is based on the fact that the flow of current into ground from an electrode system has the same path as the emission of electric flux from a similar configuration of conductors having isolated charges. For a deeply buried system-

$$R = \frac{P}{4\pi} \cdot \frac{1}{C} \qquad \ldots \qquad \ldots (3.1)$$

where P is resistivity of the earth and C the combined capacitance of the electrode system and its image.

The problem is then to find the capacitance of the complex buried electrode system. There are two important methods-

1. Howe's average potential method
2. Maxwell's method of sub-areas.

3.2. HOWE'S AVERAGE POTENTIAL METHOD:

An approximate method of calculation is used for a great many shapes of conductors, is the average potential method due to Dr. G.W.O. Howe. This consists in assuming uniform charge density over the surface of conductor and calculating the average potential. Then the approximate capacitance is taken as equal to the total charge divided by the average potential. This method is not absolutely correct from the stand point of theoretical physics as the charge distributes itself over the body of the electrode system is in such a manner as to make the potential throughout the surface of body a constant. But this method is widely used as it is a practical method.

3.3. METHOD OF SUB-AREAS:

This method can produce the desired degree of accuracy by selecting a number of sub-divisions. In most cases, a small number of subareas is sufficient for practical accuracy.

The electrode system carrying electric charge is divided into sub-areas A_i $(i = 1, 2, 3 \ldots. n)$ each of them carrying a charge density q_i $(i = 1,2 \ldots. n)$. The sub-division is so made that each sub-area is small enough to make the following assumptions.

1. The charge density q_i over A_i is essentially constant.
2. The potential V_{ij} produced by charge on A_i over the area occupied by A_i may be chosen to calculate the potential. Similarly the potential V_{ji} produced by charge on A_j over the area occupied by A_i is constant.

The following equations are then written:

$$V_{ij} = K_{ij}\, q_i \qquad \ldots \qquad .. (3.2)$$

when V_{ij} is the potential on A_j due to charge q_i on A_i. The total potential is-

$$V_j = \sum_{i=1}^{n} V_{ij} \quad = \quad \sum_{i=1}^{n} K_{ij}\, q_i \qquad .. (3.3)$$

Thus the potential of each sub-area may be computed giving n linear equations in n variables. However, since the charges are in equilibrium over the charge electrode system, the potential is constant every where on it, therefore

$$V_0 = \sum_{i=1}^{n} K_{ij} q_i \qquad \ldots \qquad \ldots (3.4)$$

where V_0 is the potential of the electrode system. The total charge Q is then given by-

$$Q = \sum_{i=1}^{n} A_i \, q_i \qquad \ldots \qquad \ldots (3.5)$$

and Q is obtained in terms of V_0. Finally the capacitance C is given by-

$$C = Q/V_0 \qquad \ldots \qquad \ldots (3.6)$$

from which the resistance of the system can be obtained.For computing the resistance of various types of electrodes, group division i.e. Electrodes in Homogenous soils and electrodes in non-homogeneous soils is made.

3.4. HEMI-SPHERICAL ELECTRODES IN HOMOGENEOUS SOIL:

The simpler electrode elements will be considered first and later some of the more complex combinations used in practice.

The simplest possible electrode is shown in Fig.$^{3.1}$a sphere in the ground which is symmetrical in all directions.

It may be entirely embedded in ground or only the lower hemisphere embedded in the half space of ground under the surface plane of the earth, a case which will be considered. If a current I flows through this electrode, spreading out radially in the ground, the current density at distance x from centre of the sphere is-

$$i = \frac{I}{2\pi x^2} \qquad \ldots \qquad \ldots (3.7)$$

According to Ohm's law such a current produces in the resistivity P of the soil an electric field strength-

$$e = Pi = \frac{P\,I}{2\pi x^2} \quad \ldots \quad \ldots (3.8)$$

The voltage, as line integral ofthe field strength from the surface of conducting sphere of radius B to the distance x, is therefore-

$$E = \int_B^x e\,dx = \frac{PI}{2\pi} \int_B^x \frac{dx}{x^2} = \frac{PI}{2\pi}\left(\frac{1}{B} - \frac{1}{x}\right) \quad (3.9)$$

Current density, field strength, and voltage in their dependence on distance, are represented graphically near the top of Fig.3.1.

The total voltage between the spherical electrode and a far distant point with $x = \infty$ is, according to equation 3.9-

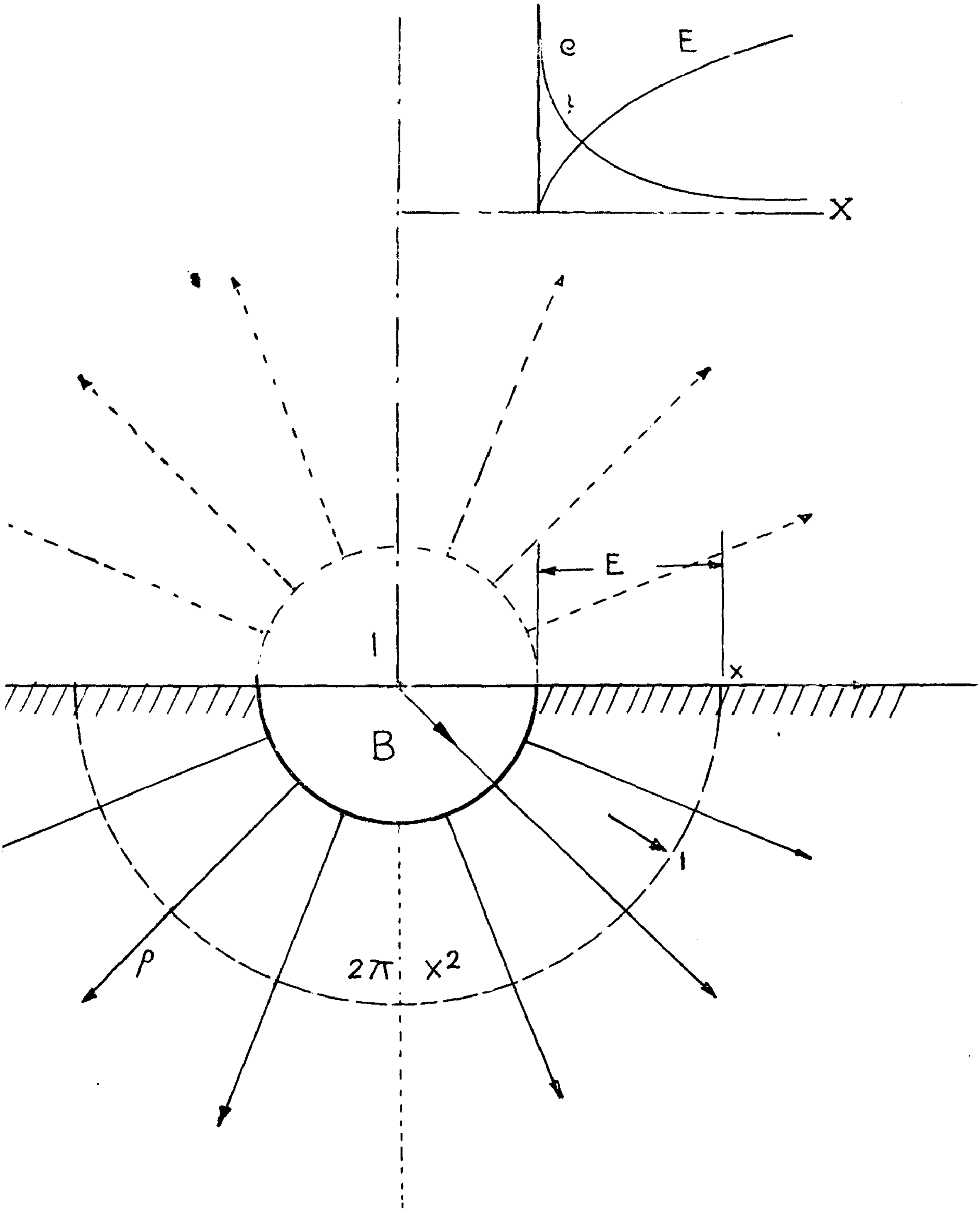
$$E = \frac{PI}{2\pi B} \quad \ldots \quad \ldots (3.10)$$

and therefore the resistance experienced by the streamlines of current diverging from hemisphere is-

$$R = \frac{E}{I} = \frac{P}{2\pi B} \quad \ldots \quad \ldots (3.11)$$

As the curves in fig.3.1 show, this resistance is distributed over the entire half space; however, the major part of it is concentrated in the proximity of the electrode.

From above, it is concluded that the resistance varies as the resistivity of the ground and as the inverse of the radius of the electrode. The absolute potential and the gradient at any external point are dependent on the distance of the point from the centre of the electrode, but not on the dimensions of the latter. The potential varies asthe inverse of distance to the centre and the gradient as the inverse of



3.1 RADIAL FLOW OF CURRENT FROM SPHERICAL ELECTRODE TO GROUND the square of the distance. The gradient falls relatively quickly. Half the total potential is absorbed at a distance from the periphery of the electrode equal to its radius.

Hemispherical electrodes are scarcely ever used in practice because the concentrated shape results in bad utilization of the metal. It is preferable to spread this over a large stretch of ground. It is seen from above that, however irregular the shape of an earth electrode, the equipotential surfaces always tend to approach a hemispherical shape, with increasing distance from the electrode in a homogeneous soil. Hence any kind of electrode will be made to correspond an equivalent hemisphere, having same grounding resistance and same current and in order to get results in a simplified manner.

3.5. BURIED SPHERICAL EARTH ELECTRODE:

In case of spherical electrode of radius r buried at a great depth in homogeneous soil, the surface offered for the discharge of current at a distance x is $4\pi x^2$, which is twice as large as with a hemispherical electrode with its flat top level with the ground. Therefore the resistance, potentials and gradients are halved.

$$i = \frac{I}{4\pi x^2} \qquad \ldots \qquad \ldots (3.12)$$

$$e = \frac{PI}{4\pi x^2} \qquad \ldots \qquad \ldots (3.13)$$

$$E = \frac{PI}{4\pi B} \qquad \ldots \qquad \ldots (3.14)$$

$$\text{and } R = \frac{P}{4\pi B} \qquad \ldots \qquad \ldots (3.15)$$

When the depth h to which the centre of the electrode is buried is finite while remaining large in relation to the radius, the non-uniformity due to the surface of ground can be eliminated by super-imposing on the electrode and ground systems their image system in relation to this surface and by making a similar current I flow from the image electrode.

For the potential at a point distance x and x' from the centres of two electrodes, it can be deduced-

$$E = \frac{PI}{4\pi x} + \frac{PI}{4\pi x'} \qquad \ldots \qquad .. (3.16)$$

In particular, if the point lies at the surface of one of the electrodes and in-so far as the distance 2h is large in relation to the radius r:

$$E = \frac{PI}{4\pi}\left(\frac{1}{r} + \frac{1}{2h}\right) \qquad \ldots \qquad .. (3.17)$$

therefore,

$$R = \frac{P}{4\pi r}\left(1 + \frac{r}{2h}\right) \qquad \ldots \qquad .. (3.18)$$

The resistance is raised in the ratio $\frac{r}{2h}$ in relation to an infinite buried depth. The potential and the gradient at the surface of the ground at a (horizontal) distance x from the point directly above the sphere are:

$$E = \frac{PI}{4\pi}\,\frac{2}{\sqrt{x^2+h^2}} \quad \text{and} \quad e = \frac{PI}{4\pi}\,\frac{2x}{(x^2+h^2)^{3/2}} \qquad .. (3.19)$$

In particular vertical above the centre-

$$E_c = \frac{PI}{2\pi h} \quad \text{and} \quad \underline{e = 0} \qquad \ldots \qquad .. (3.20)$$

The potential vertically above the centre is lower, the greater the buried depth. On the other hand, the difference of potential between this area of ground and metal structures connected to electrode increases some what with depth. Burying an electrode is thus no protection against contact with a structure connected to it.

The potential gradient on the ground surface, which is zero vertically above centre, passes through a maximum at a distance from this point equal to 0.7 times buried depth.

$$\frac{de}{dx} = \frac{\rho I}{4\pi}\left\{ \frac{2}{(x^2+h^2)^{3/2}} + -3/2 \cdot \frac{2x \cdot 2x}{(x^2+h^2)^{5/2}} \right\} = 0 \quad .. \ (3.21)$$

For maximum gradient.

Therefore $x = 0.707h$ ... .. (3.22)

Thus maximum at 0.7 times the depth.

Varn of E fr. centre outwards ?

3.6. PLATE ELECTRODES:

The resistance of plates in vertical or horizontal position respectively, according to Dwight based on average potential method is as under:

[illegible]

$$R_v = \frac{P}{8r} + \frac{P}{4\pi S}\left(1 + \frac{7}{24} \cdot \frac{r^2}{S^2} + \frac{99}{320} \cdot \frac{r^4}{S^4} + \ldots\right) \quad (3.23)$$

and

$$R_h = \frac{P}{8r} + \frac{P}{4\pi S}\left(1 - \frac{7}{12} \cdot \frac{r^2}{S^2} + \frac{33}{40} \cdot \frac{r^4}{S^4} \ldots\right) \quad (3.24)$$

where 'r' is radius of plate and 'S/2' is depth of burial. According to emperical formula by Larent-

$$R = \frac{P}{8r}\left(1 + \frac{r}{2.5h+r}\right) \quad \ldots \quad .. \ (3.25)$$

or- For infinite depth, $R = \frac{P}{8r}$

For zero depth, $R = \frac{P}{4r}$ ... .. (3.26)

Comparison of these values with those corresponding to spherical electrodes shows that a plate electrode has substantially the same resistance as a sphere of radius 1.5 times smaller.

3.7. SQUARE PLATES:

According to Dwight, the equation for reciprocal of capacitance of isolated rectangular thin plate is-

$$\left(\frac{1}{C}\right)' = \frac{2.973}{\sqrt{A}} \qquad \ldots \qquad \ldots (3.27)$$

where $\sqrt{A}$ is length of one of the sides in cm. It was pointed that $\left(\frac{1}{C'}\right)$ is too high and 8% should be subtracted.

Therefore the correct value is-

$$\frac{1}{C} = \frac{2.736}{\sqrt{A}} \qquad \ldots \qquad \ldots (3.28)$$

For plate deeply embedded in ground

$$R = \frac{P}{4\pi} \cdot \frac{2.736}{\sqrt{A}} \qquad \ldots \qquad \ldots (3.29)$$

For plate at surface-

$$R = \frac{P}{2\pi} \cdot \frac{2.736}{\sqrt{A}} \qquad \ldots \qquad \ldots (3.30)$$

According to Laurent[10], the square plate is comparable to a circular one with a radius equal to 0.6 times the side. [illegible]

The reciprocal of capacitance of an isolated thin rectangular plate as represented by Dwight[11] using the average potential method, which is an approximate solution that gives results all out 8% too high, is given by the following equation.

$$\frac{1}{C} = 2\left\{ \frac{1}{a}\log_e \frac{a+\sqrt{a^2+b^2}}{b} + \frac{1}{b}\log_e \frac{b+\sqrt{a^2+b^2}}{a} + \frac{a}{3b^2} + \frac{b}{3a^2} - \frac{(a^2+b^2)\sqrt{a^2+b^2}}{3a^2b^2} \right\} \qquad \ldots \qquad \ldots (3.31)$$

where a = length of plate in cms.

b = width of plate in cms.

The resistance of rectangular plates of different length to width ratios and buried depth are tabulated by Gross and

and Wise[12]. The method used for finding resistance is of Maxwell's method of Sub-areas.

The calculated results show that the grounding resistance decreases as plate is buried deeper in earth. As L/W ratio is increased the effects of a change in depth become less pronounced. Accordingly, for order of magnitude of depth to be used for a grounding mat, this change in resistance may be neglected if the L/W ratio is greater than 4.

3.8. LOOP-SHAPED ELECTRODE:

The resistance of a horizontal circular loop of radius r, buried at depth h and consisting of a conductor of diameter d can be expressed, according to Dwight[11] by-

$$R = 0.366 \frac{P}{2\pi r} \left(\log \frac{16r}{d} + \log \frac{4r}{h} \right) \qquad .. (3.32)$$

The second term is approximate and does not apply to extreme values of h. The comparison of resistance between a solid plate and simple ring of same diameter shows that the solid plate is not much more effective than a simple ring.

unlikely

3.9. VERTICAL RODS:

The resistance of a vertical rod with a length L and a diameter d as developed by Rudenberg[13] is-

$$R = 0.366 \frac{P}{L} \log \frac{4L}{d} \text{ ohms} \quad \ldots \quad .. (3.33)$$

The calculations were made by dividing the rod into small sectional elements between which the current is assumed to be equally distributed and using method of images. The formula developed by Dwight gives-

$$R = 0.366 \frac{P}{L} \log \frac{8L}{d} - 0.16 \frac{P}{L} \quad \ldots \quad .. (3.34)$$

The results given by these two equations agree to a close approximation.

Another formula mentioned by Laurent is quite accurate and results are quite comparable with those of Dwight's formula, is-

$$R = 0.366 \frac{P}{L} \log \frac{3L}{d} \qquad \ldots \qquad \ldots (3.35)$$

From the above equation, it can be concluded that the diameter of rod has little contribution to the resistance as it is included in logarithmic term, where as the resistance decreases more effectively with increase in length of rod.

3.10. HORIZONTALLY BURIED ELECTRODE:

The resistance of a recti-linear electrode with a length L h, and a diameter d, buried at a depth h, is expressed by- Laurent[10]

$$R = 0.366 \frac{P}{L} \left(\log \frac{3L}{2d} + \log \frac{3L}{8h}\right) \ldots \qquad \ldots (3.36)$$

The second term in brackets is suitable for moderate depths, but should be replaced by zero for infinite depth.

As calculated by Tagg[3] For length 2L, radius a & burial depth S/2,

$$R = \frac{P}{4\pi L}\left(\log_e \frac{4L}{a} - 1\right) + \frac{P}{4\pi S}\left(1 - \frac{L^2}{3S^2} + \frac{2}{5} \cdot \frac{L^4}{S^4} + \ldots\right)$$

For large values of S/L

$$\ldots \qquad \ldots (3.37)$$

and for small values of S/L-

$$R = \frac{P}{4\pi L}\left\{\log_e \frac{4L}{a} + \log_e \frac{4L}{S} - 2 + \frac{S}{2L} - \frac{S^2}{16L^2} + \frac{S^4}{512L^4}\right\}$$

$$\ldots \qquad \ldots (3.38)$$

The resistance calculated by Rudenberg when L is the length and buried to a depth h, is given by

$$R = \frac{P}{2\pi L}\left(\log_e \frac{2L}{d} + \log_e \frac{L}{2h}\right) \qquad \ldots (3.39)$$

From the above equations, it can be seen that the depth and the diameter of electrode do not have appreciable effect on the resistance of the electrode.

For various arrangements of radiating arms the resistance is calculated by Dwight[11] and it was found that the effectiveness of radiating arms decreases when their number is increased or for a given length of wire the single straight wire is the best.

3.11. NON CIRCULAR SECTION OF EARTHING CONDUCTOR:

If a flat conductor is used in place of round conductor, a some what lower resistance will be obtained with the same amount of material. The circular form of earth conductor gives the smallest perimeter for a given section and thus has the lowest capacity for discharging current. The equivalent radius of a thin tape of width a_o is-

$$a = a_o/e^{3/2} = 0.22a_o \qquad \ldots \qquad \ldots (3.40)$$

The formula is obtained by average potential method, assuming the tape to consist of a number of infinitesimal wires and to be long enough so that potential varies logarithmically with distance.

But as recommended by Laurent[10]:

$$\text{Equivalent diameter of flat conductor with width } W = \frac{W}{2} \qquad \ldots \qquad \ldots (3.41)$$

3.12. ELECTRODES IN PARALLEL IN HOMOGENEOUS SOIL:

A multiplicity of electrodes in the ground interferes with the diffusion of their partial currents in the soil and thus increases their individual resistances.

The central electrodes are more affected than the peripheral ones and the current will tend to be displaced towards the latter. These effects are small when there is a small number of electrodes and the separations are large compared with their dimensions. They are considerable when the electrodes are numerous and close together.

Above a certain degree of occupation of a ground area of a given size there is practically no gain, as regards resistance, by additional electrodes. However beyond this limit, increasing the number of electrodes reduces the current discharged by each and thus reduces the local potential gradients.

The potential gradients in close proximity to a particular electrode depend solely on the current discharged by this electrode and are only very slightly affected by the more distant electrodes.

3.13. MULTIPLE ROD ELECTRODES:

The analytical expression for large values of S/l developed by Rudenberg[13] for multiple rod electrodes is-

$$R = \frac{1}{n} \frac{P}{2\pi l} \log_e \left(\frac{2l}{a} \right) \qquad \ldots \qquad .. (3.42)$$

where n = no. of rods

l = length of rod

S = distance between the rods.

and a = radius of rod.

For S/l is small.

$$R = \frac{P}{2\pi l} \log_e \left(\frac{2l}{A} \right) \qquad .. \qquad .. (3.43)$$

where $A = \sqrt[n]{a\, S_2\, S_3\, S_4 \ldots}$

This is the equation for a single rod except the radius of rod has been changed to A.

An analytical expression derived by Schwar-z[14] which can be used for grounding rods is-

$$R = \frac{P}{2\pi n L_1} \left\{ \log_e \frac{4L_1}{b} - 1 + \frac{2k_1 L_1}{\sqrt{A}} (\sqrt{n} - 1)^2 \right\} \qquad .. (3.44)$$

where-

L_1 = length of each rod in cm.

$2b$ = diameter of rod in cm.

n = number of rods placed in area A.

k_1 is co-efficient proportion to length to width ratio of area and can be noted from curve given in fig.3.4.

GROUNDING MATS

The grounding mat is essentially a geometrical configuration in which conductor is laid horizontally under the surface in criss-cross fashion. This is used in order to have low resistance to ground and to have gradient control at the surface of earth, thus making it useful in modern substations.

The various methods for computation of grounding grid resistance evolved by different authors are given below:

3.14. METHOD OF GROSS AND OTHERS:

Using the equation for resistance -

$$R = \frac{P}{2\pi} \frac{1}{C}$$

where C is the capacitance of the electrode system and its image w.r.t. the surface of earth. Assuming grid is buried near the surface.

The author made use of above relation and calculated the capacitance of grid by average potential method.

The analytical expression for resistance for a one mesh square grid is-

$$R = \frac{\rho}{2\pi W} \left\{ 0.0316 - 0.0189 \log_e \frac{rd}{A} \right\} \text{ if } \frac{d}{W} \ll 1 \qquad \text{.. (3.45)}$$

where,

W = width of grid in ft.

r = radius of conductor in ft.

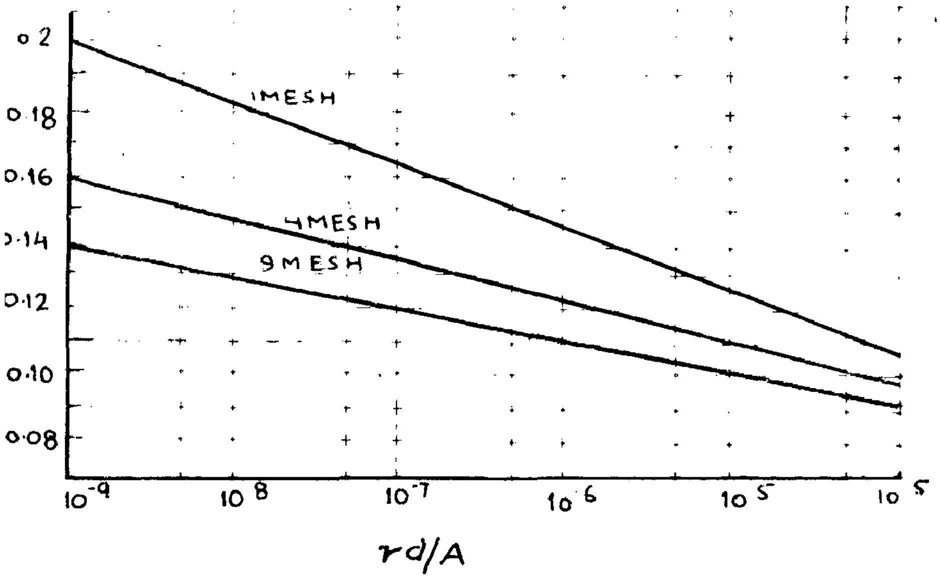
d = distance between grid and its image = 2 h.

A = Area of the grid in square feet.

As the number of meshes of a grounding grid is increased, the grounding resistance is lowered, with the optimum condition being attained for a buried flat plate. The grounding resistance decreased with depth. As the length to width is increased, the effects of a change in depth become less pronounced[12].

By employing Maxwell's method of sub-areas, the capacitance of a rectangular grid can be calculated. The results given by the authors are as under:-

1. The resistance of a ground grid decreases with the increase in area enclosed.
2. The resistance decreases with increase in the diameter of wire used. It is not a linear variation, but decreased more slowly as the wire size increases.
3. The resistance decreases with depth to which the grid is buried. The resistance decreases quite rapidly first and then very slowly as the depth is increased.
4. The resistance of grid decreases with increasing



1·2 RESISTANCE TO GROUND—UNIVERESAL CURVE FOR GROUNDING GRIDS.

number of meshes; the decrease is quite rapid in the beginning, but slow after 16 meshes. The useful

The useful universal curve for grounding grids is given in fig.3.2 from which the resistance to ground as function of the number of meshes, the area, depth and size of conductor can be obtained.

3.15. METHOD BY McCROCKLIN AND WENDLANDT:

The mathematics involved in calculating the resistance of a grounding grid is of complex nature, and even an approximate solution is not obtained easily. The authors obtained experimental test data by measuring the resistance to ground of different types of plates andgrids in water, having a definite length to width ratios and depth to width ratios. It was seen that the capacitance is proportional to the length or width, so long as the length to width ratio is constant. Using the test data and equation $R = \frac{P}{2\pi} \cdot \frac{1}{C}$, the results of tests are presented in the form of curves. The curves shown in fig.3.3and and 3.4 give the values of k_1 and k_2 for various ratios of L/W, S/W and A/W, which when used in the formula below, give the resistance-

$$R = \frac{k_1\, k_2 \cdot P}{10.16 \cdot \pi \cdot W} \qquad \ldots \qquad \ldots (3.46)$$

where-

W = width of grid in inches.

L = length of grid in inches.

S = depth of grid below surface in inches.

A = spacing between wires in grid in inches.

The equation have the restriction that W/d = 945, where d is diameter of wire in inches. W/d = 650 gives the resistance

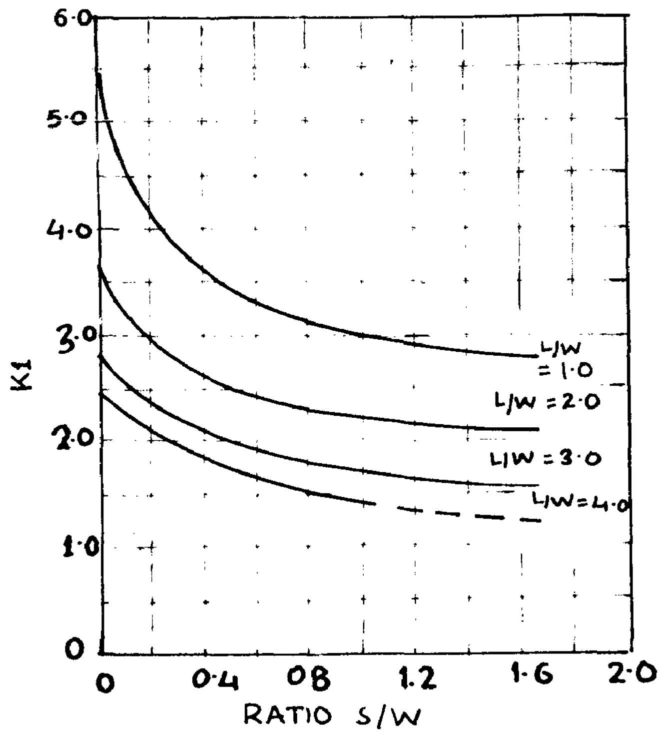


FIG 3·3 The variation of K_1 with variation of depth-width ratio

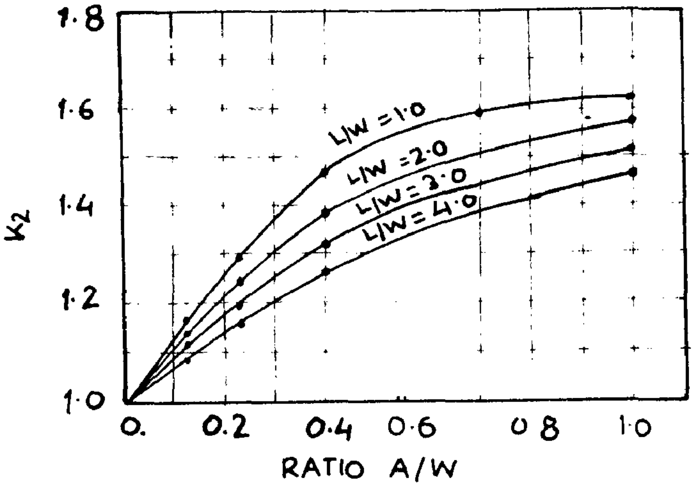


FIG 3·4 A plot of K_2 against ratio of spacing between the wire of grid to width of grid.

5% below the value obtained for W/d = 945 and W/d = 1500 gives the resistance which is 5% higher. Hence this equation can not give correct results for all values of W/d.

3.16. SCHWARZ'S METHOD:

The method developed by Schwarz giving analytical expression for resistance of grounding systems is based on the Howes average potential method. The resistance of an intermeshed network is-

$$R = \frac{P}{\pi L} \left(\log_e \frac{2L}{a} + k_1 \frac{L}{\sqrt{A}} - k_2\right) \quad \ldots \quad \ldots (3.47)$$

where-

P = soil resistivity, ohm centimeter.

L = Total length of connected conductors, cm.

$a' = \sqrt{a.2Z}$ for conductor buried at depth of Z cm or

= 'a' for conductor at earth's surface.

2a = diameter of conductor in cm.

A = Area covered by conductor in sq.cm.

k_1 & k_2 are the co-efficients given in the fig.3.5 and 3.6 as functions of length to width ratio.

As most of the grounding systems consist of grids and rods, the resistance of rod bed is given by equation (3.44).

The combined resistance is ofcourse lower than either component alone, but still higher than plate, and is given as under:

$$R = \frac{R_{11}\,R_{22} - R_{12}^2}{R_{11}+R_{22} - 2R_{12}} \quad \ldots \quad \ldots (3.48)$$

where,

R_{11} = resistance of grid.

R_{22} = resistance of rods in parallel.

R_{12} = R_{21} = Mutual resistance between the two systems.

SCHWARZ'S CO-EFFICIENTS

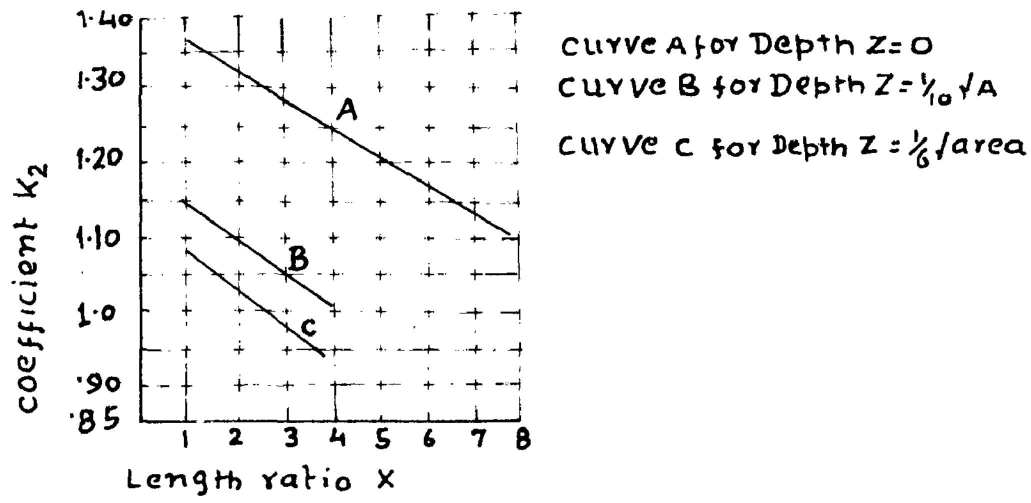


FIG 3·5 VALUES OF CO-EFFICIENT K_1 AS FUNCTION OF LENGTH TO WIDTH RATIO OF AREA.

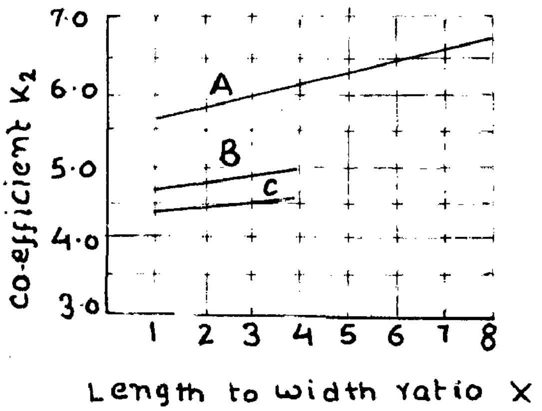


FIG 3·6 VALUES OF CO-EFFICIENT K_2

✓

$$= \frac{P}{L} \left(\log_e \frac{2L}{L_1} + k_1 \frac{L}{\sqrt{A}} - k_2 + 1\right) \quad \ldots \qquad .. (3.49)$$

3.17. LAURENT'S METHOD:

A very simple method employed by Laurent,[10] giving the resistance of a substation with an average radius r in meters erected on homogeneous ground and having a length L in meters of buried wiring can be expressed approximately by the equation-

$$R = \frac{P}{4r} + \frac{P}{L} \quad \ldots \qquad .. (3.50)$$

where,

P is the resistivity in ohm-meters.

The first term is the resistance of a superficial plate having a radius r. The second term recognizes the fact that the resistance of a grid is more than that of a solid plate, and that this difference decreases as the length of conductor increases, becoming zero as the solid plate condition is reached.

3.18. EARTHING ELECTRODES IN NON-HOMOGENEOUS SOIL:

As already shown in Chapter 2 that a non-homogeneous soil can be, to a good approximation, represented by two stratification model, i.e. a superficial horizontal layer with a depth d and resistivity P_1 and of homogeneous sub-soil with resistivity P_2. Using this concept the resistance formulae for various electrodes given below:

3.19 RESISTANCE OF SMALL ELECTRODES:

If the electrodes can be compared to a hemispherical electrode having radius r, sufficiently small as compared with thickness d of above layer, its resistance has the approximate value:-

$$R = \frac{P_1}{2\pi r} + 0.366 \frac{P_1}{d} \log_e \frac{P_1 + P_2}{21} \qquad .. (3.51)$$

The first term will be the resistance of hemisphere in a homogeneous medium having a resistivity P_1. The second term, which is independent of radius r, provided that it is small is additive or subtractive accordingly as as P_2 is higher or lower than P_1.

The resistance of wire may be based on the potential at mid-point. The resistance[8] obtained for wire at surface is-

$$R = \frac{P_2}{\pi l} \log \frac{l}{a} - \frac{P_2 - P_1}{\pi l} \left\{ \log_e \frac{2}{\gamma ba} - E_1\left(\frac{bl}{2} \right) \right\} \quad \ldots \quad \ldots (3.52)$$

where,

E_1 is exponential integral-

$$E_1(u) = \int_u^{\infty} \frac{e^{-u}}{u} \cdot du$$

and $\gamma = 1.781$

when $\frac{bl}{2} = .2$, the following approximation may be used-

$$E_1\left(\frac{bl}{2}\right) = \log_e \left(\frac{bl}{2}\right) - \frac{bl}{2}$$

therefore,

$$R = \frac{P_1}{2\pi l} \log_e \frac{l}{a} + \frac{P_2 - P_1}{\pi l} \frac{bl}{2} \quad \ldots \quad \ldots (3.53)$$

when $\frac{bl}{2} \geqslant 1$, E_1 function may be neglected and the resistance is then-

$$R = \frac{P_1}{\pi l} \log_e \frac{2/\gamma b}{a} + \frac{P_2}{\pi l} \log_e \frac{l}{2/\gamma b} \quad \ldots (3.54)$$

where,

$b = \delta/2d$.

d being the depth of top layer and δ a constant which depends on the resistivity ratio as follows[8]

P_1/P_2 =	100	10	1	.1	.02
δ =	2	1.84	1.16	.4	.12

3.20 VERTICAL ROD:

The upper layer has a resistivity P_1 and thickness of this layer is h. The resistivity of second layer is P_2 and the reflection co-efficient is defined as $\frac{P_2-P_1}{P_2+P_1}$. In case the sub-soil more conductive than surface and the driven rod is a long vertical rod having length H in soil of resistivity P_1 and a length(L-H) in subsoil of resistivity P_2. It can be assumed that the ground is homogeneous and has a resistivity P_2, by simply reducing the length H situated in the resistant layer in proportion to P_2/P_1.

this line.

When sub-soil more resistant than the surface, the current have difficulty in spreading in depth and runs superficially to distances which become all the greater as P_2 gets higher. Thus results in increase in resistance as compared with homogeneous soil with a resistivity P_1.

When a driven rod is inserted in the upper layer to length l, the effect of the second layer on the resistance of the rod may be calculated approximately by using the average potential method and combining this with the method of images. The rod is combined with its image above the surface of earth giving a source of length 2l and carrying a charge q/cm.length. Now it is known that the potential at any point in the systen can be obtained by calculating that due to charge itself and adding to it the potential due to its images in the interfaces between the layers.

The resistance[3] of rod becomes-

$$R = \frac{P_1}{2\pi l}\left\{\left(\log_e \frac{4l}{a} - 1\right) + \sum_{n=1}^{n=\infty} \frac{u^n}{2} \log_e \frac{(nh/l)+1}{(nh/l)-1}\right\} \quad \ldots \quad \ldots (3.55)$$

The first term in the expression is the resistance of rod of length l driven into soil of resistivity P_1, and the second term represents the additional resistance due to the second layer.

When the length of driven rod l is greater than h, it is no longer possible to assume that the current flows uniformly from the rod all along its length, due to change of resistivity in soil surrounding the rod, It is, however, a reasonable assumption that the current density is inversely proportional to the resistivity. Based on the above assumption, the resistance is-

$$R = \frac{P_1}{2\pi l} \left\{ \frac{1+u}{(1-u)+2u\,\frac{h}{l}} \right\} \left\{ \log_e \frac{2l}{a} + \sum_{n=1}^{n=\infty} u^n \log_e \frac{2nh+l}{\{(2n-2)h+l\}} \right\} \quad \ldots \quad .. (3.56)$$

3.21, MULTIPLE ELECTRODES:

When an extensive ground is constructed by driving a large number of short rods into surface layer, the resistance is affected substantially in the same manner by variation in resistivity with depth as in case of buried wire. The resistance of a single rod is determined mainly by the surface resistivity where as that of great number of rods depends to a considerable extent on the variation of resistivity with depth. Thus, when the resistivity increases with depth, the effect of mutual resistance between rods is greater than for uniform earth and, as the number of rods is increased, the combined decreases less rapidly than for uniform earth. On the other hand, when the resistivity decreases with depth, the opposite effect is observed, i.e. the resistance decreases more rapidly than for uniform earth as the number of rods is appreciable, it is because of a fairly small thickness of the upper layer combined with a very low resistivity of lower layer, in which case it is preferable to drive one or a few rods into lower layer.

3.22. GROUNDING GRIDS:

In case of a grid buried in non-homogeneous soil, the two layers as previously given can be assumed having resistivity P_1 and P_2. When the sub-soil is better conductor than the surface, in the resistance equation (3.50), P_2 should be introduced for the term corresponding to the effect of the plate, and P_1 for that corresponding to the local potential drops in neighbourhood of the electrodes, The equation[10] then becomes-

$$R = \frac{P_2}{4r} + \frac{P_1}{L} \qquad \ldots \qquad \ldots (3.57)$$

But this equation is very approximate, as it does not consider the thickness of the resistive layer.

When the sub-soil is highly resistive, the term $\frac{P_2}{4r}$ corresponding to the effect ofthe soil plate becomes much larger and the term $\frac{P_1}{L}$, corresponding to the local voltage drops in the neighbourhood of the buried conductors, is even more negligible.

Thus local potential drops, however, retain approximately the same values in the absolute sense as if the ground were homogeneous throughout and had a resistivity P_1. The resistance itself, depends practically on P_2 only.

A more rigorous solution by Gross and Thapar to the problem of non-homogeneity of soil is finding the apparent resistivity of soil as given in the Chapter 2. Once the apparent resistivity is determined, the problem reduces to that of a uniform soil with resistivity equal to apparent resistivity. The apparent resistivity depends not only on the soil conditions but also on the size of grid. The change in L/W from 1:1 to 4:1, increases $\frac{P_a-P_1}{P_2-P_1}$ by 0.02, which is not very significant. Therefore, if the shape of grid area is somewhat different from rectangle, there would not be introduced appreciable error by considering it a rectangle of area A.

CHAPTER - 4

POTENTIAL GRADIENTS AND HUMAN SAFETY

4.1. GENERAL:

Safety of human beings is of prime important in the design of grounding grids. Under fault conditions, the flow of current to earth will result in gradients within and around the substation. Unless proper precautions are taken in design, the maximum gradients along the ground surfaces may be so great, under very adverse conditions, as to endanger a man walking there. Also, dangerous potential differences may sometimes exist, during a fault, between structure or equipment frames which are 'grounded' and the near by earth. So low station ground resistance is not a guarantee of safety. There is no simple relation between the resistance of the ground system as a whole and the maximum shock current. A station of relatively low ground resistance may be dangerous under some circumstances. On the other hand, some stations with very high resistance are safe, or can be made safe, by careful design.

In addition to the magnitude of the local gradients, other factors enter into safety problem. These include such things as duration of shock, body resistance, physical condition of the individual, probability of contact, current magnitude, frequency, waveform and phase of heart cycle at the instant of shock[16].

It is difficult to perform experiments on human beings, beyond a certain value to know the effect of electric shock on the heart. Tests on the effect of shock on heart action of various animals revealed that the current is proper shock criterion instead of voltage. Starting from zero the current can be gradually increased to a value of about 0.9mA. at 50 cycle A.C. and it was found that the average man feels tr lingl-ing effects caused by stimulation of the sensory nerve ending in the skin. This point is known as the threshold current of sensation. As the current is increased (upto 15mA at 50 cycles) the subject is unable to control muscles affected, which means the person concerned would be unable to remove himself from the source of shock. It may be possible, however, at this stage, to use other muscles not affected by the current flow to effect the release. If the muscles affected are those controlling the respiratory system, breathing is likely to stop, and if the person can be removed from the source of electric shock, breathing can be restored provided the maximum current for fabrillation is not exceeded. If it is, respiratory inhibition results which may last for extended periods after the current is removed, unless artificial respiration is applied at an early stage, death would result in many cases. Current beyond this value may cause ventricular fibrillation, which is an interruption of normal heart action and which will result in death, because once fibrillation is established it is not likely to cease naturally before death. This condition is an un-co-ordinated asynchronous contraction of the ventricular muscle fibres in contrast to their normal co-ordinated and rhythmic contraction, is caused rather by abnormal stimulation rather than any damage to the heart.

4.2. THE ELECTRICAL SHOCK HAZARD ANALYSIS:

Physiological effects of shock in order of rising current flow (steady state) as given by Geiges[17] are:

1. Perception 0.1 to 0.2 milliamperes.
2. Muscular contraction-inability to release cont-act

(6-20 milliamperes for adult).

3. Unconsciousness may occur here.
4. Fibrillation of heart (100 milliamperes)
5. Respiratory nerve block-cessation of normal breathing.
6. Burns and hemorrhage.

4.3. CURRENT DURATION, MAGNITUDE AND FREQUENCY IN RELATION TO SHOCK:

In design of grounding grids, the 50 c/s fault current is of more concern. In the case of lightning surges the human body seems able to tolerate very high currents, perhaps of the order of hundreds of amperes due to very short duration.

In case of single impulse condition the safety current should not exceed 300 mA after 0.003 seconds and should not exceed 5mA after 0.2 sec. If the time required for current to decrease 5 milliamperes is between 0.1 and 0.2 sec., the quantity passing through the body in that time should not exceed 4 millicoulombs; if between 0.03 and 0.1 sec it should not exceed $75T - 350T^2$ millicoulomb[17].

The effects of different current magnitudes for one or more seconds give that threshold of perception is generally agreed to be at current flows of about one milliampere. For shock for one second or more, threshold 25 percent higher for 25 cycles, and five times as high for direct current.[18]

The maximum safe current is established at the let go current of 99.5 percent of large group at 60 c/s for men and women are 9 and 6 milliamperes respectively, where let-go currents are defined as the maximum current an individual can tolerate and still be able to release his grasp of an energized conductor by using muscles directly stimulated by that current.[19] As mentioned earlier, death may occur due to heart condition known as ventricular fibrillation. Hence the threshold of ventricular fibrillation is of major concern. The figure of 100 mA is based on extensive experiments at Columbia University on animals having body and heart weights comparable to man, with maximum shock duration of 3 seconds.[18]

4.3.1. Duration:

It is agreed generally that much higher currents can be tolerated without causing fibrillation if the duration is very short. According to Ferris, King[18] and others, the threshold varies inversely but not regularly with duration being most sensitive to change as duration of one heart beat is approached. Dalziel[16] analyzing the Columbia University tests, concluded that 99.5 percent of all men could withstand, without ventricular fibrillation currents determined by the equation-

$$I_k^2\, t = 0.027 \quad \ldots \quad \ldots (4.1)$$

$$\text{From which } I_k = \frac{0.165}{\sqrt{t}} \text{ amps.} \quad \ldots \quad \ldots (4.2)$$

where I_k is r.m.s. current through the body in amperes.

t is time duration of shock in seconds.

0.027 is an empirically derived energy constant.

The above equation results in values of 165 mA for 1 second and 520mA for 0.1 sec. (6 cycles). Equation (4.2) is based on tests limited to three seconds duration. It is not valid for very long duration, as some values of current can be tolerated indefinitely.

Experiments show the effect on threshold, of the time of shock initiation with respect to the phase of heart cycle, for shocks of different duration.[20]

Equation (4.2) indicated that much higher currents can be allowed where fast operating protective devices can be relied upon to limit the fault duration. Discretion is needed as to whether to use the clearing time of regular high speed relays, or that of back up protection, as the basis for calculation. A preference be made for the former due to the very low probability that relay malfunction will coincide with all other adverse factors necessary for accident.

4.4. RECLOSURES:

In the name of safety again, it is very important to note the effect of reclosure after a fault, which is so common under modern operating practice. A single 'fast' automatic reclosure would usually result in a second shock initiated within a little less than a half second from the start of the first, with little oportunity for the victim to free himself in the interval, because according to experiments performed by Dalziel[21], the time required to release the wire is 0.2 to 0.4 second; when the current is 2 to 4 mA.above the let-go current threshold. With manual reclosure, where the interval would normally be from several seconds to a few minutes there would be greater possibility that the victim could avoid another shock on reclosure.

According to Ferris, King and others,[18] the succesive shocks have no cumulative effect on susceptibility of the heart to fibrillation. This conclusion is based on the exhaustive studies in which repetitive shocks were applied at five minutes interval. The conclusion is also based on test shocks repeated as many as ten times in a short interval, but it is not known that the same would be applicable for very short intervals.

The limitations of present knowledge suggest that some allowance should be made for reclosure shocks. It should at least vary from 0.75 to 1.0 second, which is release time with safety factor 2 based on 60 cycles freezing current.[21]

4.5. BODY RESISTANCE AND CURRENT PATH:

Resistance measured from hand to both feet in 10 inches of salt water with arm immersed to elbow is 400 to 600 ohms at 60 cycles alternative current.[22]

Body impedance can range from a few hundred to several hundred thousands of ohms. Five hundred ohms selected as practical minimum for moist conditions; for dry indoor conditions, limited contact area and skin not punctured, this increases to 1500 ohms[17]. Resistance of skin removed is about 300 ohms. independent of voltage. Body resistance varies between 600 to 800 ohms (bare feet on damp soil) and 5000 to 10,000 ohms (dry shoes on dry ground) normal value order of 2000 ohms for fairly good contact. From two hands to two feet, with damp skin 1800 ohms; between two feet (dry skin), 2300 ohms; with nailed shoes and damp feet, 6500 ohms. Assumed for calculations, 2000ohms, though with skin punctures resistance could be reduced to 500 ohms.[48]

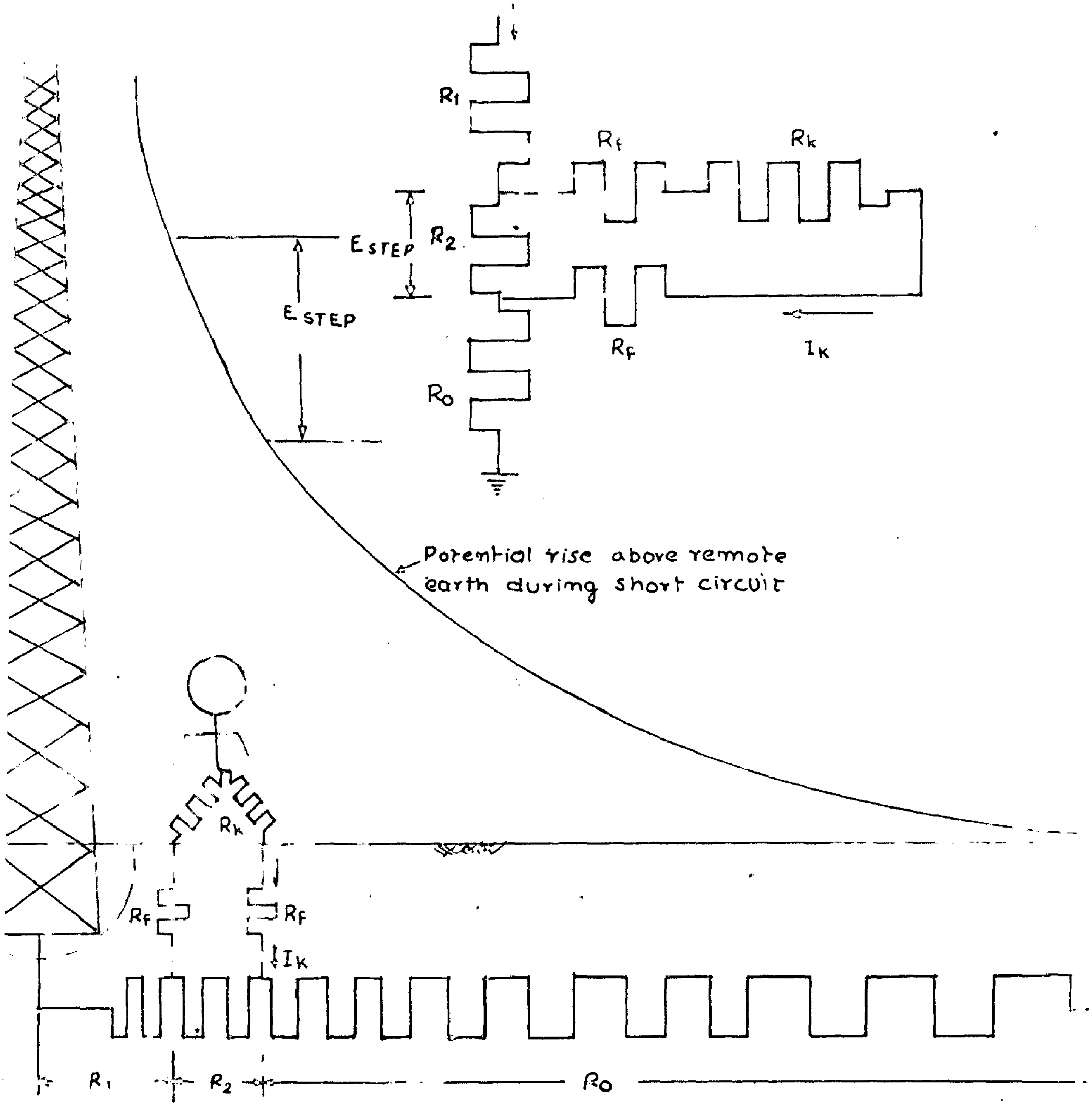
From the above the body resistance is assumed to be 500 ohms for the most worst conditions.

The most dangerous current is that when it takes the path through parts of body containing the most vital organs including the heart. So the current flowing from one foot to another is far less dangerous as compared to hand to one or both feet. The tests by Loucks[23] confirmed the fact that much higher foot-to-foot than hand-to-foot currents are required to produce the same current in the heart region, the ratio could be as high as 25 to 1.

4.6. STEP, TOUCH AND TRANSFER VOLTAGES:

After having the knowledge of tolerable body currents, it is possible to calculate the maximum possible values of step, touch and transfer voltages from safety point of view and which are required for safe design of grounding systems.

Fig. 4.1 shows the equivalent circuit for a step or foot-to-foot contact. The potential difference shunted by body in this case is limited to maximum value between two accessible points on the ground separated by the distance of one pace, which will be assumed to be one meter. Circuit constants include the resistance of ground system R_1 plus R_2 plus R_o, the resistance of shoes; the resistance of R_F of the ground immediately under each foot; and body resistance R_k. The resistance of the shoes is uncertain and for damp leather may be very small. It will therefore assumed to be zero. Resistance of the ground just beneath the feet, may affect appreciably the value of body current, a fact which may be most helpful in some difficult situations. The foot can be considered equivalent to a superficial plate electrode with a radius of about eight centimeters, and the ground resistance can be calculated in terms of resistivity P_s of the soil near the surface. It has been determined that the resistance of two feet in series (step contact) is approximately 6 P_s ohms, taking one foot flat and other not completely flat down, while walking[10]. But according to Ontario Hydro Research news[24], the experiment shows that the ground resistance of one foot R_f is equal to seven inches



s 4.1 STEP POTENTIALS NEAR GROUNDED STRUCTURE diameter circular plate, or 2.8P ohms, and the resistance of two feet in series is approximately 1.8 R_f. For practical purposes, the resistance R_f in ohms for each foot can be assumed to be 3 P_s.[25]

The proper value to use for body resistance (including skin and internal resistance of body) is much difficult to establish. According to Dalziel[32], the value standing in 10 inches of salt water with arm immersed uptc elbow were 400 to 600 ohms for both direct and alternating 60 cycles current. According to the same author[19], the let-go current for 99.5 percent of men is 9 mA. with 21 volts hand to hand and 10.2 volt hand to feet at 60 cycles. Alternating current, giving the resistance 2330 ohms and 1130 ohms respectively. According to Laurent the usual body and skin resistance for 50 cycles per second. Alternating current, is 3000 ohms. A value of 1000 ohms is the most reasonable value according to Guide AIEE 1961[25], in order to avoid an unreasonable compounding of safety factors on one side and more optimistic value on other side. Therefore 1000 ohms value will represent the resistance of body from hand to feet and also from one foot to another.

Tolerable potential difference between any two points of contact can be calculated in terms of the circuit constants and allowable body current. By Thevenin theorem, the body current between these two points will be equal to that which the preexisting voltage would cause to flow through the body resistance in series with the external network connecting the points of contact.

Therefore, the tolerable step potential is-

$$E_{step} = (R_k + 2\,R_f)\,I_k$$
$$= (1000 + 6P_s)\,\frac{0.165}{\sqrt{t}}$$
$$= \frac{165 + P_s}{\sqrt{t}}\ \text{volts} \qquad \ldots \qquad \ldots (4.3)$$

According to Niemann[26], step potential is given by the equation:

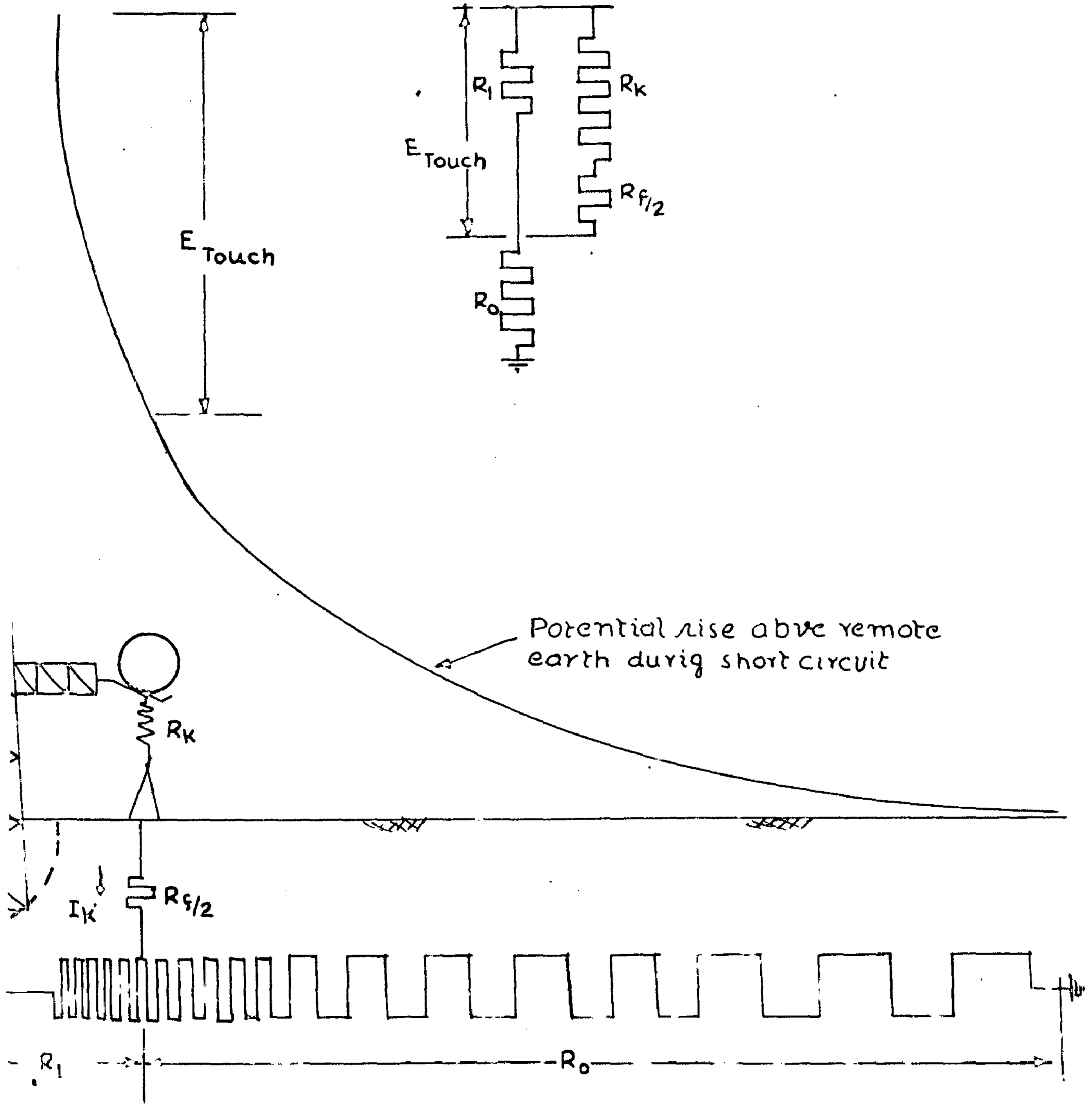
$$E_{step} = 0.1\ Pi\ \text{to}\ 0.2\ Pi \qquad \ldots \qquad \ldots (4.4)$$

where i is the current per unit length, whose average value is the total fault current divided by the total length of buried ground conductor in meters, however, for critical areas near perimeter, author suggests increasing this by 20 to 30 percent. According to Laurent[10], $E_{step} = 0.1$ to $0.15\ Pi$, for usual values of conductor size, burial depth and spacing.

Touch Voltage:

The fig.4.2 shows the equivalent circuit for a 'touch' or hand-to-both feet contact. If the objects touched were grounded immediately below it, the maximum earth potential difference intercepted would be that which could occur over a distance along the ground equal to the normal maximum horizontal reach, again approximately one meter. The circuit constants include the resistance of the ground electrode system($R_1 + R_0$), the contact resistance of hand, R_f the resistance of ground immediately under each foot and the body resistance R_k. As assumed earlier, the body resistance R_k as 1000 ohms and foot resistance $3\ P_s$. Therefore the tolerable touch potential is-

$$E_{touch} = (R_k + \frac{R_f}{2})\,I_k$$
$$= (1000 + 1.5\ Ps)\left(\frac{0.165}{\sqrt{t}}\right)$$



4.2 TOUCH POTENTIALS NEAR GROUNDED STRUCTURE

$$= \frac{1000 + 0.25P_s}{\sqrt{t}} \qquad \ldots \qquad \ldots (4.5)$$

According to Laurent[10] the touch potential-

$$E_{touch} = 0.6 \text{ to } 0.8\ Pi \qquad \ldots \qquad \ldots (4.6)$$

According to Niemann[30], deeper burial decreases 'step' potentials, but increases touch or contact potentials.

Some times, the objects touched may be grounded more remotely, and this fact must be taken into account. One example of this is the 'Mesh Voltage' which is a type of touch contact. Therefore touch voltages from a grounded structure to the centre of a rectangle of grid mesh are used, rather than touch voltages at a horizontal distance of one meter from the grid wire, since there are so many possibilities that an object touched, while standing at a distance of more than one meter may be connected directly or indirectly to the grid. The special case of touch voltage will be referred to as 'Mesh voltage'. It will, in general, have a greater value than the touch voltage at a distance of one meter from grid wire.

According to Laurent[10]-

$$E_{mesh} = Pi \qquad \ldots \qquad \ldots (4.7)$$

where,

P = Resistivity in ohm-meters.

i = Current in Amperes per meter of buried conductor, flowing into ground.

This is an approximate value as given by Laurent, because it is based on average ranges of conductor diameter, depth of burial and grid conductor spacing (French practice). Due to the non-uniformity in the flow of ground current per unit length of buried conductor, an irregularity must be taken into account.

Therefore instead of above equation, AIEE safety guide[25] gives-

$$E_{mesh} = K_m \, K_i \, P \, \frac{I}{L} \qquad \ldots \qquad \ldots (4.8)$$

where,

K_m is a co-efficient which takes into account the effect of number n, spacing D, diameter d, and depth of burial h, of the grid conductors and is given by the equation.

$$K_m = \frac{1}{2} \log_e \frac{D^2}{16hd} + \frac{1}{\pi} \log_e \left(\frac{3}{4}\right) \left(\frac{5}{6}\right) \left(\frac{7}{8}\right) \ldots \text{etc.} \qquad (4.9)$$

where number of factors in second term being two less than the number of parallel conductors in the basic grid.

K_i is an irregularity correction factor, to allow for non-uniformity of ground-current flow from different parts of grid. The emperical curve gives the value of K_i-

$$K_i = 0.65 + 0.172n \qquad \ldots \qquad \ldots (4.10)$$

which is based on Koch's experiment.

where n is the number of parallel grid conductors in one direction i.e. excluding cross connections.

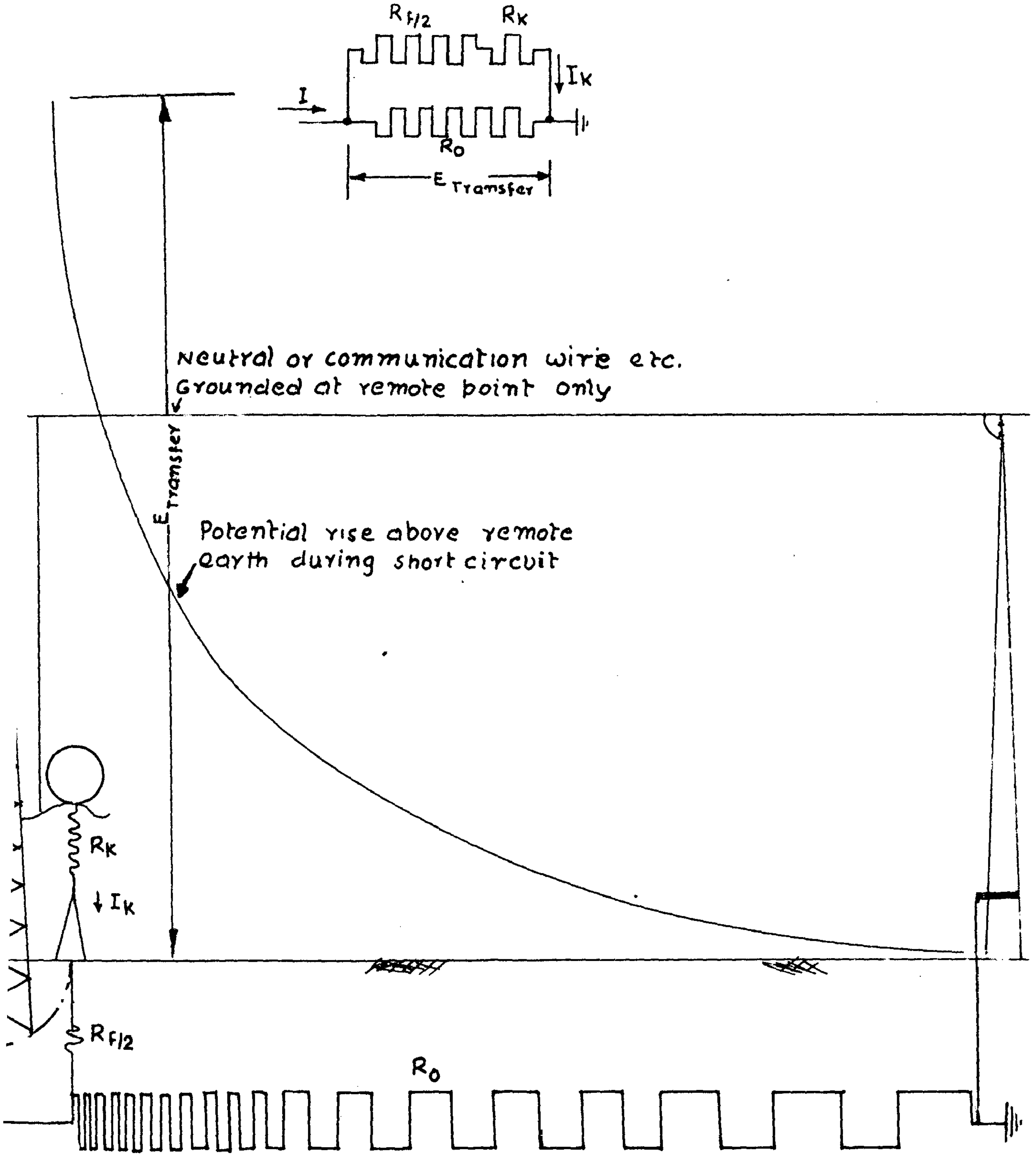
P is the average resistivity of ground in ohm-meters.

I is the maximum total r.m.s. current, in amperes, flowing between ground grid and earth, as adjusted to allow for decrement and future system growth.

L is the total length of buried conductor, in meters.

Similarly a more realistic approach to the step voltage, taking into account depth of burial and spacing as given by AIEE guide 1961[25] gives-

$$E_{step} = K_s \, Ki \, P \, \frac{I}{L} \qquad \ldots \qquad \ldots (4.11)$$



G 4·8 HAZARD FROM TRANSFERRED POTENTIAL

where,

K_s is a co-efficient which takes into account the effect of the number n, the spacing D, and the depth of burial h of the grid conductors, is given by equation-

$$K_s = \frac{1}{\pi}\left(\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{2d} + \frac{1}{3d} \;\ldots \text{etc.}\right) \quad .. (4.12)$$

The total number of terms with in the brackets being equal to the number of the parallel conductors in the basic grid, excluding the cross connections.

Transferred potential is also a special case of touch potential as shown in fig.4.3. The hazard occurs when a person standing within the station area touches a conductor grounded at a remote point or a person standing at a remote point touch a conductor connected to the station ground mat. The shock voltage is essentially equal to full voltage rise of ground mat under fault conditions.

4.7. POTENTIAL GRADIENTS IN CASE OF NON-UNIFORM SOIL:

In case of non-uniformity of soil resistivity, the results may be quite different, giving unexpectedly high local gradients. The potential gradients are practically the same in the close vicinity of small electrodes, as in the soil were homogeneous and had a resistivity P_1. The effect of subsoil becomes more and more pronounced the greater the distance. In case, subsoil is more conductive than the surface, the potentials and the gradients around an electrode will very quickly reach the values which would correspond to homogeneous ground with the same resistivity as that of subsoil[10]. The gradient is steeper for pipe or vertical plate, but in case of horizontal plate or strap, an initial lowering in value of the gradient occurs upto the moment when the thickness of the layer is approximately equal to the depth of electrode; at this moment an abrupt increase takes place approaching the value corresponding to uniform resistivity.

When sub-soil is more resistive than the surface and the thickness of upper layer is less than depth of burial, the surface potential gradient is less than for soil of uniform resistivity. When the thickness of upper layer is greater than the depth of burial, the gradient is approximately same as for soil of uniform resistivity.

The potential gradient around an electrode in soil having two layers of which the resistivities are in the relation of 100 to 1, never exceed by more than 50 percent the gradient corresponding to a uniform soil.[27]

(a) Assuming the earth in the vicinity of grid to be represented by two layers, the surface layer of certain depth 'h' and resistivity P_1, and a lower layer of infinite depth and resistivity P_2, it has been shown by Thapar[28], that the maximum step (assuming pace of one meter) and maximum mesh potentials are given by the equation.

$$\text{Max.}E_{\text{step}} = \int_r^1 G_x\,dx = \frac{P_1 \cdot i}{\pi}\left\{\sum_{k=1}^{n}\left\{\log_e \frac{(k-1)D+1}{(k-1)D+r} + \sum_{m=1}^{\infty} u^m \log_e \frac{\{(k-1)D+1\}^2+(2mh)^2}{\{(k-1)D+r\}^2+(2mh)^2}\right\}\right\} \quad \ldots (4.13)$$

$$\text{Max.}E_{\text{mesh}} = \int_r^{-D/2} G_x\,dx = \frac{P_1 \cdot i}{\pi}\left\{\sum_{k=1}^{n}\left\{\frac{1}{2}\log_e \frac{\{(k-1)\ D-D/2\}^2+r^2}{\{(k-1)\ D+r)^2+r^2} + \sum_{m=1}^{\infty} u^m \log_e \frac{\{(k-1)D-D/2\}^2+(2mh)^2}{\{(k-1)D+r\}^2+(2mh)^2}\right\}\right\} \quad \ldots (4.14)$$

where,

n is number of conductors.

r is radius of conductors.

D is horizontal spacing between conductors.

u the reflection co-efficient $\frac{P_2 - P_1}{P_2 + P_1}$

(b) If the change in resistivity of soil with depth below the surface is continuous. The resistivity can be considered as a continuous function of depth below the surface.

$$P = F(z)$$

where P = resistivity of the soil

z = depth below the surface

F = continuous function to represent the actual variation of resistivity.

then δ the total current density at point P at distance X from conductor one, due to n conductors and their images, is in the direction of X and is given by-

$$\delta = \frac{1}{\pi} \left\{ \sum_{k=1}^{n} \left\{ \frac{1}{(k-1)D+x} + \int_{F(o)}^{F(\infty)} \frac{(k-1)D+x}{\{(k-1)D+x\}^2 + \{2\,\phi\,(P)\}^2} \cdot \frac{dP}{P} \right\} \right\} \quad \ldots \quad \ldots (4.15)$$

The potential gradient at X is-

$$G_x = F(o) \cdot \delta$$

$$\therefore E_{max}(step) = \int_r^1 F(o)\ \delta\ dx.$$

and $$E_{max}(mesh) = \int_r^{-D/2} F(o)\ \delta\ dx.$$

The integration involved in the above equations is not simple and the use of an analogue or digital computer is recommended.

CHAPTER - 5

MATERIALS FOR THE GROUNDING GRID

5.1. GENERAL:

Due to the scarcity of copper and the tight import policy of Government of India, thought is being given to alternative materials for the grounding grids. As the grounding grid provides safety to equipment and personnel and improvement in quality of service, it is very important that the grid should have long life or in other words, the conductor material of grid should have the following qualities:

(i) High resistance to under-ground corrosion.

(ii) Mechanically strong to withstand any physical damage.

(iii) Low electric resistivity, so that there should not be dangerous local potential differences.

(iv) Able to resist fusing and deterioration of electric joints under the most adverse combination of fault current magnitude and fault duration to which it might be subjected.

(v) Economical to use.

For the above qualities, a study of different materials, from the view point of underground corrosion, suitable size and finally economics is a necessity.

Due to high resistance to under-ground corrosion and low electric resistivity, copper is the most common metal in use for grid conductors. The life of grid was taken as a sufficient number of years, so long as conductors are of adequate size and not subjected to mechanical injury. But the advantage of copper as cathodic proves a great loss to all the under-ground buried steel with which it is connected, by forming galvanic cells and hastening corrosion of latter.

The table gives the open circuit potential in earth volts to copper electrode.

Metals		Equilibrium potential
Magnesium	..	-2.7V
Aluminium	..	-2.0V
Zinc	..	-1.1V
Iron	..	-0.7V
Lead	..	-0.4V
Copper	..	0.0

As steel, iron, zinc and lead are all anodic to copper in earth and when an electric circuit exists where copper is in combination with one or more of these other metals, there will be current from them into earth and hence to copper. Copper is not damaged by this action, but usually all metals are. For every ampere year lead loses about 73 lbs., zinc about 24 lbs. and iron or steel about 20 lbs.[46]

To eliminate corrosion of other materials, the most obvious solution is to use only one of these metals in the under-ground' because most of the facilities in the ground are made of iron or steel. It would appear that a grounding network made entirely by steel conductor would be satisfactory. It requires 15 times current or 225 times power to protect steel out of steel and copper combination than exclusively steel.[46] So to protect steel in the ground, all steel is the only economical solution.

Steel was used exclusively for the grounding networks at Hosensack and 160 other substations of pennsylvania. Its advantages are:

1. Elimination of galvanic action between dissimilar metals in earth.
2. Ability to obtain material for grounding when copper is scarce.
3. Reduction in cost of grounding system.

Aluminium has been used less frequently for grounding grids. In such cases relatively high purity electric conductor grade is more satisfactory than alloys. Commercially pure aluminium contains 99.0 - 99.3% aluminium and rest iron and silicon with minor amounts of copper. Use of aluminium like use of steel avoids contributing to the corrosion of under-ground pipes etc. However, the aluminium itself may corrode in certain soils. Alternating corrosion of aluminium may also be a problem under some conditions. Therefore its use is limited due to corrosion and relatively low strength.

5.2. UNDERGROUND CORROSION:

Corrosion is an electro-chemical phenomenon. It is always accompanied by an inter-change of current between the corroding conductors and the environment. The corroding metal is at higher potential than its surroundings and accordingly there will be a flow of electricity away from metal, leaving it an ionised (oxidised) state. Chemical combination with oxygen from the surroundings must occur simultaneously for electtical balance. Stray-current corrosion occuring where current is discharged from a buried conductor,is referred to as anodic corrosion.

Corrosion associated with but not directly due to stray currents may be encountered on structures in sections where currents enter the structure as result of accumulation of certain electrolysis products which cause corrosion, is referred to as cathodic corrosion. An interchange of current may also be set up by galvanic action due to direct contact between conductors of different metals or due to variation in contact potential along conductor with respect to environment, resulting from heterogeneities in the environment or in conductor material. Such corrosion is called heterogenic corrosion. Galvanic corrosion does not require the presence of dis-similar metals. Anodic and cathodic areas may form on a metal surface because of variation in structure of metal or its environment. A conductor buried in earth may be exposed to varying concentration of oxygen. Other conditions being equal, the iron surface tends to become anodic where oxygen is excluded and cathodic where oxygen is present, with the result that galvanic corrosion removes iron from the most deeply buried surfaces.[29]

Direct currents from external source some times flow in the grounded metal structure and cause corrosion where the current flows from the metal into the soil.

5.3. CORROSION BY SOIL:

To study the corrosion of grounding mat in soil, is a problem of major importance. The deterioration of the exterior of metals exposed to soil, but not to stray electric currents is usually called soil corrosion and attributed to soil characteristics. It is generally assumed that the corrosiveness of a soil controls the service life of a metal in soil, which in turn depends also upon the thickness of metal, the area exposed and maintenance applied. When the grid is buried for a number of years, corrosion by soil should be given due importance for selection of material for grounding.

The characteristics of corrosive soils are poor aeration, high values of acidity, electrical conductivity, salt content and moisture content. Poorly aerated neutral soils are favourable to development of bacteria which accelerates corrosion. Well aerated soils especially those derived from lime stone are not corrosive. Some characteristics indicate a soil is corrosive and others indicate opposite, is a common feature. Thus making it difficult to fell from soil analysis whether the soil is corrosive or not. But it has been observed that the more corrosive the soil is, the lower the electrical resistivity and the non-corrosive soils have high resistivity[29] as given in table. Also when total acidity is the chief variable, the relation between acidity and corrosion is more evident.

Soil Resistivity and Corrosivity

Range of soil Resistivity ohm-meter.	Class
0-10	.. Severe corrosion
10-25	.. Severely corrosive
25-50	.. Moderately corrosive
50-100	.. Mildly corrosive
Above 100	.. Very mild corrosion.

Tests conducted by K.H. Logan by burying direct metals in soil indicate that copper corrodes much more slowly than steel under most soil conditions.

Copper is resistant to the corrosive action of most soils. However, soils with a high content of organic matter or alkaline soils in which ratio of chlorides and carbonates to sulphate is high, may be corrosive. Copper should not be embedded directly in cinders or in tidal marshes where it may be subject to attack by sulphur compounds.

For steel, when the samples of the commonly used ferrous materials are buried side by side, they will corrode at somewhat different rates&given pit depth is a function of area of specimen. The choice of material to be exposed to a definite soil condition should not be based on its average performance in many soils.

The extent of attack that occurs on aluminium alloys buried under-ground varies greatly, depending on the soil composition and climatic conditions. In dry sandy soils corrosion is negligible. In wet, acidic or alkaline soils, attack may be severe. Specimens in the form of panels 3 x 9 x .064" thick were buried to a depth of 2 ft. in soil for five years in clayey soil gave the following results.[29]

	Well drained soil			Marshy soil		
Alloy	Max Depth of attack in inches	% change in Tensile strength	Remarks	Max. Depth of attack in inches	%change in Tensile strength	Remarks
2S-½H	.0017	-1	Mild general etching	.028	-7	Pitted
Steel	.0647	-27	Completely perforated at 3 spots	.019	-17	Pitted

Steel is less corroded in marshy soils due to less presence of oxygen in soil.

Although aluminium does not contribute to the corrosion of other under-ground materials, but it is less frequently used for grounding grids as its under-ground corrosion and cathodic protection is complex and requires chemical analysis of soil.

5.4. ALTERNATING CURRENT CORROSION:

Laboratory and field investigations were made to determine the corrosive effects of alternating current upon metals. The corrosion rate of metals will be increased by flow of alternating current. There are several factors that will comprise the total effect that the passage of alternating current will have upon metal corrosion. Some of those factors will be, rectification by the oxides caused by corrosion; a d.c. component of a.c. current, polarization so that one electrode will act as a cathode, an acceleration of corrosion caused by galvanic couples; and effect of a.c. itself.[33]

5.5. CORROSION OF STEEL OR IRON IN SOILS HAVING SULPHER COMPOUNDS:

In case of soils of high sulphide content, oxidation of reduced inorganic sulphur compounds may greatly increase corrosion of iron and steel. The microbilogical corrosion under neutral conditions is highly intense. In case of slightly alkaline soils no serieus microbilogical corrosion can be observed, even if the soil resistance is low due to the high water content of the soil. In periods of year i.e. summer, when aeration increases, the resistivity of soil may also increase, so instead of increase in corrosion rate, it may decrease.[34]

5.6. PROTECTION OF CONDUCTOR MATERIAL FROM CORROSION:

In order that the grounding system may have long life, the protection of conductor material from corrosion is of prime importance. Corrosion of copper in soils was taken as negligible and usually no protection was provided. But rate of corrosion of steel and aluminium is much more than that of copper ordinarily, the following are the possible treatments of protection:

4.7. SOIL TREATMENT:

The soil treatment may take three forms:

(i) The addition of chemicals to neutralize corrosive soil properties. As in case of soil having high sulphide content, changing the neutral soil to little alkaline will decrease the rate of corrosion largely. It can also help in accelerating the formation of protective films.

(ii) Replacement of corrosive soil next to conductor by less corrosive soil.

(iii) Adjustment of Moisture content in soil. In case (i), increasing moisture content may decrease the corrosion rate in summer months. In some other case, the water drainage may help preventing corrosion.

But in all cases due consideration should be given to the other factors in case of grids such as change in grounding resistance and potential gradients.

5.8. PROTECTIVE COATINGS:

Any corrosion resistant coating which is to be applied must be current conducting. Some utilities have tried to avoid disadvantage of copper as being cathodic to other metals and causing corrosion, by tinning the buried copper to reduce the potential cell. This reduces potential with respect to zinc and steel about 50 percent and eliminates the potential with respect to lead, as tin being slightly sacrificial to lead.

Zinc is the only mettalic coating extensively used for under-ground service. In some soils, zinc carbonate provides a partly protective coating, in othersafter corrosion has punctured the zinc, the iron beneath is cathodically protected. The duration of protection of the iron by zinc is usually proportional to thickness of zinc coating. In case of pipes, it was found that steel pipes do not corrode appreciably until most of zinc has been removed. In forty five, locations zinc coating with 2.8 oz. zinc/sq.ft. (4.7 mils) protected steel from rusting or pitting for an average period of 10 years. Coatings with at least 2 oz. zinc per sq. ft. are recommended. Zinc coated pipes fail most rapidly in those soils in which steel corrodes quickly. The uncoated steel corrodes about three times as rapidly as the galvanized pipes.[29] The zinc coating only due to its short life can not be depended upon.

5.9. CATHODIC PROTECTION OF STEEL:

Corrosion is caused on the equipment situated under-ground by exposure to air and other gases; water and corrosive chemical fluids, and soil in which there is a combination of salt-bearing water and oxygen. Cathodic protection may theoretically be applied in any of these situations. However, protection against corrosion by the first two conditions may usually be provided by less costly means, though the approach to the categories differ radically.

The economy can be judged by weighing the investment and operating cost for cathodic protection either using individually or in conjunction with other approaches such as coatings. Pit or point corrosion is the most dangerous type of corrosion, in which only small area is attacked, but the rate of penetration is high. Uniform and local corrosion which also occur in some degree are less dangerous. For all the remedy is cathodic protection. Polarizing a corroding metal to ~~open~~ the open circuit potential of the anodes establishes an equipotential surface which, in accord with electro-chemical principles, is no longer subject to corrosive attack. The current required to polarize to this potential increases with corrosion rate.

For most metals the anode open-circuit potential is not directly measurable because of the continuing corrosion which polarizes the potential to some more noble or cathodic value. The potentials, which were measured, were in fact corrosion potentials and not equilibrium potentials.

However standard potentials can be checked by general thermodynamic data for reactions involving the metal, and the equilibrium anode potential can be calculated. In aqueous systems, including soil environments, the corrosion product is a hydrous oxide or hydroxide of metal. Hence if solubility product and standard potential E_o of hydroxide is known, the open-circuit anode potential E can be readily calculated[44] as given under:

$$E = E_o - \frac{0.059}{n} \log_e (M^{n+})$$

where $(M^{n+}) = \frac{\text{Solubility product}}{(OH^-)^n}$

and $(OH^-) = n\,(M^{n+})$ in accord with

$(M^{n+})(OH^-)_n - M^{n+} + n(OH^-)$

Values calculated for a few representative metals are listed in table.

Calculated Minimum potential for cathodic protection

Metal	Std.potential V	Solubility product $M(OH)_2$	Potential	
			Standard Hydrogen scale V	Copper-saturated $Cu.SO_4$ V
Iron	0.440	1.8×10^{-15}	0.59	0.91
Copper	-0.337	1.6×10^{-19}	-0.16	0.16
Zinc	0.763	4.5×10^{-17}	0.93	1.25
Lead	0.126	4.2×10^{-15}	0.27	0.59

These are applicable in any environment such as in natural waters or soils for which the corrosion product is hydroxide.

In case of steel, assuming no exceptional corrosion condition, the metal must be depressed to a value of 0.85V with respect to copper-copper sulphate half cell. This corresponds usually to current density of 2-3 mA/ft^2 for buried structures.[45]

The impressed potential may be supplied from either a d.c. source or by a galvanic couple set up between the metal to be protected and a more electro positive metal such as magnesium, aluminium or zinc. In both cases, an anode must be provided in soil. An inexpensive anode i.e. scrap metal is used in case of an external d.c. source, because it will be corroded. In general, the impressed potential will exceed the corrosion potential some-what, so that there will be flow of current into the metal to be protected or in other words the under-ground equipment is made cathodic to soil and is thus protected from corrosion.

From economic point of view, it is very important to choose suitable type of source of electric current. The basic sources are divided into the following categories[30].

(i) Externally generated current normally supplied as a.c. and rectified.
(ii) Current which is generated on location
(iii) Galvanic anodes and
(iv) Storage batteries.

In selecting a source, the controling considerations are amount of power required, soil resistivity, topography and accessibility for maintenance purposes. In case of grids first two factors are of importance. Dependability of the power source is also important, for intermittent operation of a cathodic protection system gives unsatisfactory results.

Galvanic anodes find their best field of usefulness where only a small current is called for e.g. for the protection of coated equipment. They can hardly ever compete with generated power for the protection of large surfaces or of exposed or poorly coated metals. The use of galvanic anodes is not advisable in soils of high resistivity- 30 ohm-meter is taken as upper limit for magnesium or aluminium and 12 ohm meter for zinc anodes. Magnesium due to its high driving potential relative to iron, is desirable where there is a high corrosion potential and high resistivity. Zinc is most useful where the corrosion conditions are less drastic and where soil resistivity is fairly low, but it has the advantage of offering high anode efficiency. Zinc will not lead to the considerable degree of over protection which often gives rise to excessive magnesium consumption, especially in low resistive soils. Aluminium is intermediate between magnesium and zinc in its properties. The anode efficiency has been stated to be nearly equal to that of zinc, but its driving potential is below that of magnesium. On price basis, aluminium scrap compares favourably with the other two metals used widely in galvanic protection. Such a price comparison of course, be based on the amount of metal dissipated per useful ampere year. This increases in the order- aluminium, magnesium and zinc.[30] The anodes should be installed at lowest locations available, at depths at least as great as the metals being protected[47] Sacrificial anodes gradually expend themselves, so that replacement becomes necessary.

The basic data required for designing a cathodic protection includes the dimensions of equipment to be protected, together with the material, extent of protection by coating the geometrical figure, the soil resistivity at grid site and at site where the electrodes are to be protected,& The minimum protection voltage or alternately the minimum current density and maximum protection voltage. The needed potential data measurements include determination of potential differences in following systems- grid to soil, metal to anode and IR drops.

The position and design of protective anodes in the soil is of considerable importance. Improper grounding of anodes is the greatest source of power loss in the entire cathodic protection system. Resistance should be low and anode placing must be selected for best distribution of current to all the corroding areas which are to be protected. A multiplicity of anodes at fairly close spacing is preferred.

The anode made of iron or steel scrap, carbon or graphite rods or of magnesium or aluminium, or zinc, must be surrounded by coke breeze or loose soil treated with chemical to raise the conductivity in the immediate vicinity of anode. Moisture content should also be kept sufficient throughout, so that current resistivity of soil surrounding it may not rise.

Finally cost justification is most important. Consideration must be given to life of grid, (because it cannot be repaired or replaced) cost of maintenance & thickness of protective film. These advantages must be evaluated and balanced against the cost of cathodic protection systems and their operation so that the most economic long-term solution may be provided for the installation.

In regard to corrosion and cathodic protection of grounding grid conductor the following points have to be considered.

(i) Steel is most useful in high resistivity soils due to low corrosivity and a coating of 2.8 oz./sq.ft. of zinc saves the steel from corrosion completely for 10 years. Corrosion of steel is three times the corrosion of galvanized steel.

(ii) Copper has got disadvantage of causing corrosion to all nearby structures, cables, pipes etc. ~~and a much~~

What [illegible]

(iii) Aluminium is most useful in dry sandy soils. Corrosion of steel is more rapid than aluminium in such soils.

(iv) Copper should not be used in cinders or tidal marshes where it is subjected to attack by sulphor compounds and where chloride and carbonates to sulphates ratio is high.

(v) Sacrificial electrodes should be used for low resistivity soils. From economic point of view the preference is aluminium, magnesium and zinc.

(vi) Use of aluminium as a grid material and sacrifical electrode demands soil analysis.

(vii) For high resistivity soils and large grid areas, rectifiers may be used.

5.10. SIZE OF CONDUCTOR:

The criteria for choosing the size of conductor as mentioned earlier is (i) it should resist fusing (ii) Mechanically rugged (iii) should not contribute to dangerous local potentials. The principle on which the conductor size is based, is that whole of heat generated with the flow of earth fault current in short duration is stored in the conductor material and it should be able to withstand it. The duration of fault current is till the protective relays operate and isolate the faulty system.

From thermal considerations, the conductor size mainly depends upon (a) Ground fault current (b) Time duration of fault (c) Material of conductor (d) Type of joints (bolted or welded). The minimum conductor cross-section (as given in detail in Appendix) is given by the following formula:

$$a = \sqrt{\frac{S}{K}} \quad \ldots \quad \ldots (5.1)$$

where a is cross-section per unit current or mm^2/Amp.

S is fault duration in seconds.

K is constant which is based on different materials.

For copper K = 2.87×10^4
Aluminium = 0.789×10^4
and Steel = 0.584×10^4

Mechanical ruggedness will set a practical minimum size. The AIEE Committee in 1954 recommended minimum sizes of 1/0 and 2/0 copper for brazed and bolted joints respectively. But a large number of sizes used in industry are 4/0 copper as minimum for mechanical reasons i.e. 107.2mm^2. But proper size can be kept on basis of local conditions. The minimum size of steel and aluminium conductors for some mechanical (tensile)strength would be 61 mm^2 and 195 mm^{2}respectively. Magnitude of fault current and their duration set the size of steel conductor, where as mechanical ruggedness sets size of copper and aluminium.[32]

The next factor which fixes the size of conductors is that the conductor size should be such, that it is not contributing to local potentials.

The potential difference is nearly negligible as compared to total rise of grid potential. If ever some difference occurs, it will be more at the centre (the points from where current flows) and have tendency to send more current. But in actual conditions, the boundary has tendency to send more current, so the above affect will be compensated.

The final approval of size of conductor is/to be taken keeping in view the under-ground corrosion. Tests conducted on steel and aluminium are only for 10 to 15 years period for studying corrosion, which is much shorter than proposed life of grid. So a regular protection is required or allowance for corrosion must be given, the latter will help in decreasing the resistance and potential gradients of the grid.

5.11. ECONOMICS FOR GRID MATERIAL:

The cost of copper grid is 3.4 times than that of aluminium grid and 8.9 times than that of steel grid. Also aluminium grid is costier than steel grid by 2.65 times as calculated in Appendix I. The cost comparision is without due consideration to corrosion of material in soil. In case of copper, corrosion of material is supposed to be negligible, which is not the case with aluminium and steel grid. Therefore the cost of latter rises due to cost of protection against under-ground corrosion. The protection provided is cathodic protection in the corrosive soils for the grounding grid material.

The cost of cathodic protection consists of investment and operating cost with due consideration to the life of grounding grid, which is assumed to be 50 years and can depend upon the importance of station. The investment consists of cost of scrap iron to be buried for 50 years and cost of source of electric current. The cost of scrap iron used as calculated in Appendix 3, is Rs. 3.92A to 5.89A (A is surface area of grid conductor in m^2), which according to Thapar[32] is less than 50% of the steel in grounding grid. The cost of providing rectifiers etc. for the cathodic protection may be assumed 10% of cost of steel in grounding system. The operating cost as given in Appendix 3 is Rs.$(35.7 \text{ to } 80.8) \times 10^{-3} A^2$, which is less than 50% of cost of steel in grounding system.[32] Therefore cost of cathodic protection in most corrosive soils is less than 110% of the cost of steel in grounding system. Thus the cost of copper grid is still nearly four times than that of steel grid with cathodic protection. If aluminium is used as grid material and cathodic protection is provided against under ground be

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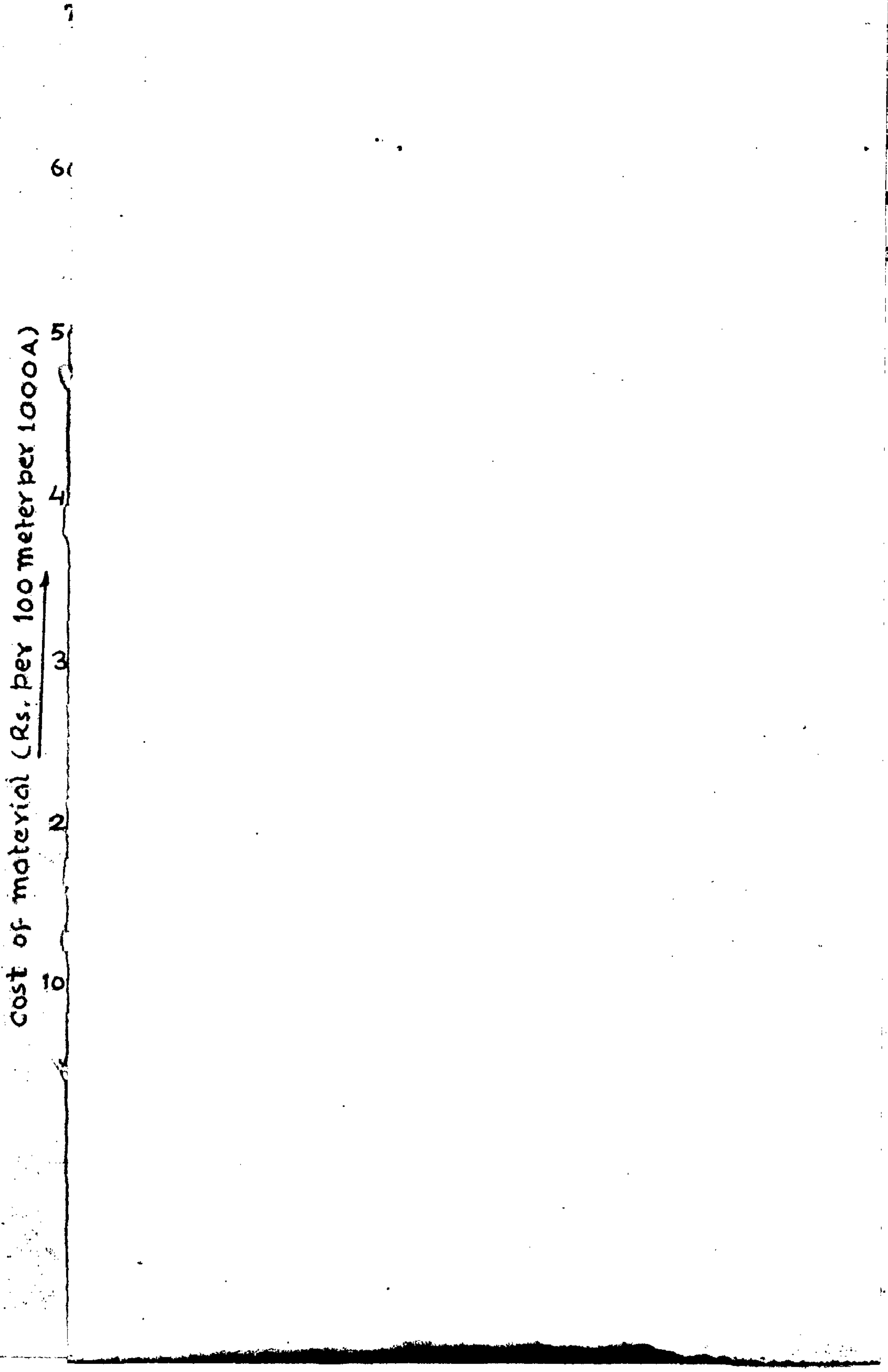

CHAPTER - 6

DESIGN CRITERIA FOR GROUNDING GRIDS

6.1. GENERAL

The grounding system aims at providing safety to operating personnel and public and the provision of connection to earth of the neutrals of transformers, generators and other power equipments, which can be achieved by connecting to ground all the metal parts, switches and instrument transformer secondaries etc. and neutrals of transformers and generators. This leads to a network of connecting wires in the earth and when buried in a regular pattern or geometrical figure taken the name as grounding grid. Therefore, in most high-voltage switch yards grounding systems are formed by a grid of horizontal buried conductors. The following advantages gives the reasoning for its wide use:

1. Due to large fault currents, the total potential rise of grounding system is far from safe for human contact, because of difficulty in obtaining low resistance in each case. The grid solves this problem, by having control of local potentials and eliminates this hazard.

2. No ordinary single electrode is adequate to provide needed conductivity and current-carrying capacity in a station of any size. When several electrodes are connected to each other and th structures, machine frame and circuit neutrals, the result is necessarily a grid.

The various considerations in the design of grounding grids are:

6.2. GROUNDING RESISTANCE:

It is important from safety considerations, to keep down

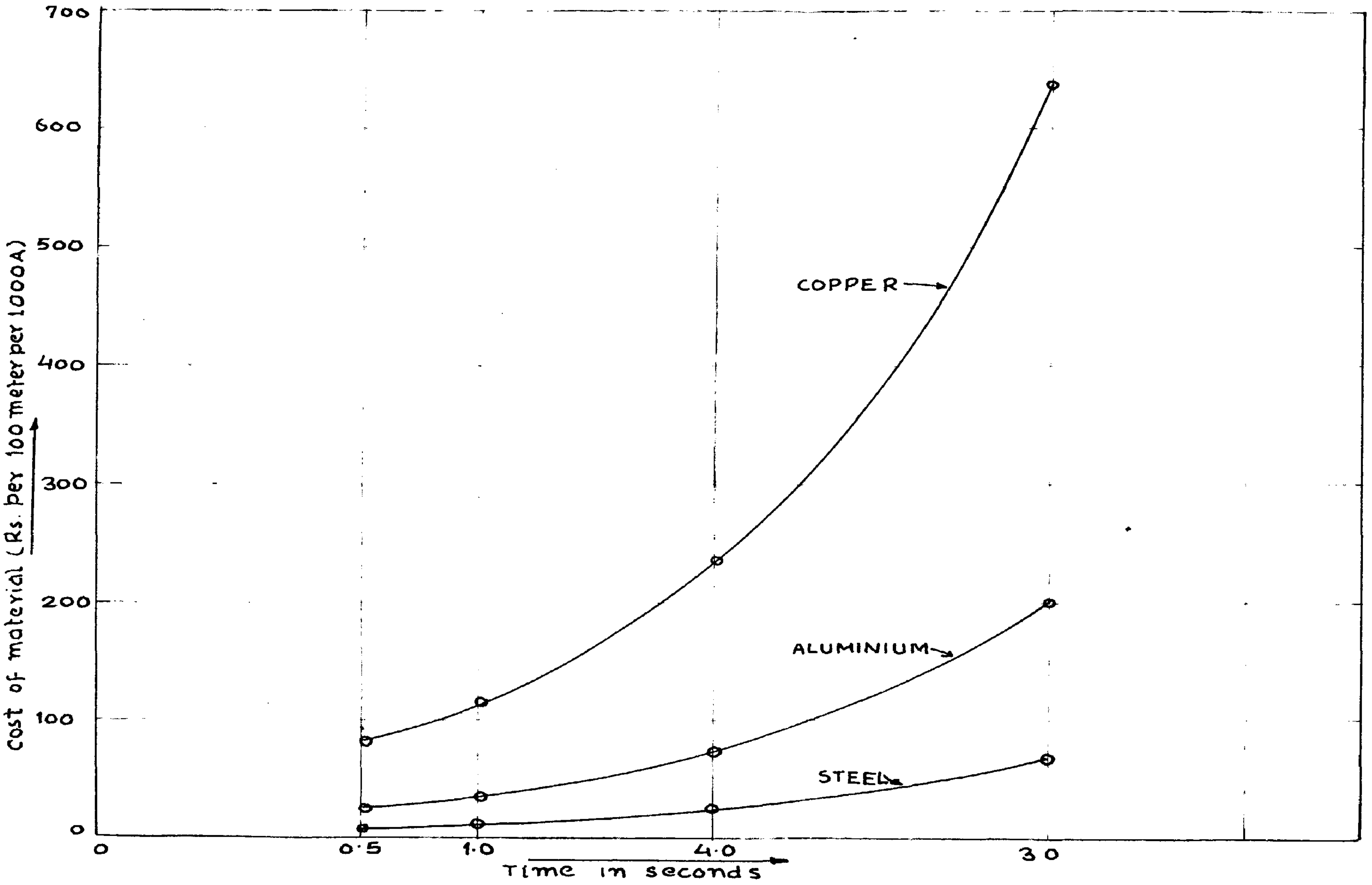

FIG 5.1 VARIATION OF COST OF DIFFERENT MATERIALS WITH VARIOUS FAULT DURATIONS

the magnitude of the total ground grid potential rise at the time of a fault. It is also important to have sufficient fault current to operate the relays at the time of a fault in order to have proper clearing of ground faults. These would necessarily require adoption of as low a ground resistance as would be practicable. Reduction of ground resistance would call for a wider area of ground grid, more length of buried conductors and would therefore involve increased cost. Choice of a suitable value of ground resistance would, therefore, assume an economic problem in which cost considerations should be taken into account while keeping in view the technical requirements. The maximum value of resistance of grounding system as recommended by various authorities is as below:

(i) According to R.W. Ryder[40]
  (a) Generator stations 0.5 ohms or less
  (b) Transformer stations (over 100 KV) 1.0 ohm or less.

(ii) According to United States Department of Interior Bureau of Relamation in large power plants and sub-stations 1 ohm or less.

(iii) According to AIEE Committee report on station grounding in large stations and sub-stations: 0.25 ohm to 1.0 ohm.

(iv) The U.S.S.R. design standard No.4 (1961) gives the maximum value of ground resistance for large power stations and sub-stations as one ohm, although 0.5 ohm limit is the usual practice in U.S.S.R.

6.3. FAULT CURRENT:

The determination of correct value of ground-fault current plays an important part in the design of grounding grid because of the fact that the total rise of grid potential, cross-section of conductor and potential gradients depend on this value. The following steps are involved in determining the correct value of ground fault current for use in station grounding system design calculations.

(a) The determination of the possible type of ground fault which will result in greatest flow of current between the ground grid and surrounding earth and hence the greatest is ground grid potential and largest local gradients in the sub-station area. This step gives no difficulty when a simplified diagram is made to represent the actual situation. Any over-head ground wires should also be included which are connected to the station ground system or transformer neutral. This on neglecting, provides extra safety.

(b) The determination of maximum symmetrical r.m.s. value I" of this ground fault current, by computation or network analyzer study, flowing between the station ground grid and surrounding earth at the instant of fault initiation. The maximum symmetrical r.m.s. value I" of ground fault current may be determined by using the following equation:

$$I'' = \frac{3E}{3R+3R_f + (R_1 + R_2 + R_0) + j(X_1'' + X_2+X_0)} \text{ amps.} \quad .. (6.1)$$

$$\text{or } I'' = \frac{3E}{X_1'' + X_2 + X_0} \text{ amps.} \quad ... \quad .. (6.2)$$

because the effect of resistance terms in the equation is negligible for practical purposes.

where,

I'' = symmetrical r.m.s. value of ground fault current at instant of fault initiation in amps.

E = Phase-to neutral potential in volts.

R = Estimated resistance to earth of local station ground system in ohms.

R_f = Estimated minimum resistance of fault itself in ohms.

R_1, R_2 & R_0 = Positive, negative and zero sequence resistance in ohms per phase.

X_1'' = Direct axis positive-sequence reactance (sub-transient) ohms per phase.

X_2 & X_0 = Negative and zero sequence, reactance in ohms per phase.

(c) Applying a correction factor, where appropriate, to allow for the effect of direct current off set and alternating and direct current decrements. This factor is necessary, because the short circuit occurs at random with respect to the voltage wave. Moreover, the shock contact may exist at the moment the fault is first initiated. Hence, to allow for the most severe condition, it is necessary to assume a 100 percent offset asymmetrical wave of ground-fault current for the duration of the shock. Since the experimental data on the fibrillation threshold is based on symmetrical sine waves of constant amplitude, it is necessary to determine an r.m.s. value of a simple sine wave current I, which is equivalent to the more complex asymmetrical fault current wave. The decremental factors[25] useful in determining the effective value of fault current at various times, after fault initiations.

Shock and fault duration		Decrement Factor
T		D
Second	Cycles (60 cycles A.C.)	
0.08	½	1.65
0.1	6	1.25
0.25	15	1.10
0.5 or more	30 or more	1.00

For intermediate values of fault duration, decrement factors may be obtained by linear interpolation. For closely spaced successive shocks (as from reclosures), the decrement factor to be used, should be corresponding to the duration of the shortest single shock, even the time 't' used elsewhere in the calculations is based on the sum of the individual shock durations.

(d) Applying a correction factor, where appropriate to allow for future increase in fault currents due to increase of the system capacity or due to new interconnections. If no margin is provided in original ground system design the grid might become unsafe after some-time and instead of adding a new grid, it will be much cheaper to consider the increase in the original design. Usually this factor is taken as 1.5[25] which is considered sufficient to allow for future growth.

6.4. TIME OF CLEARING OF FAULTS:

High speed clearing of faults help the safety of design in the following ways:

1. Probability of shock is greatly reduced by high speed fault clearing as compared to situations in which fault currents can persist for several minutes or possibly hours.

2. In case of happening of such coincidence, the chance

of severe injury or death is greatly reduced, as shown by tests if the duration of current flow through body is very brief.

Another important advantage of fast clearing is the reduction of cost of grid due to smaller cross-section used from thermal stability point of view as shown in figure.

6.5. RESISTIVITY OF SOIL AT STATION SITE:

The variation of the resistivity of soil is between wide limits. As the resistance of the grounding system and the potential gradients are directly proportional to the resistivity of soil, so it is necessary to obtain accurate data on the soil resistivity and on its variations at station site in order to design the grounding system most economically.

In order to cover the area adequately at the station site, resistivity measurements are to be conducted at several positions, with different probe spacings and an earth resistivity curve is to be plotted. The tests are to be conducted at least over one full year, as the variation in resistivity is due to season also. More details are given in Chapter 2.

6.6. PRELIMINARY DESIGN OF GROUNDING GRID:

After knowing the factors i.e. type and resistivity of soil at station site, maximum ground fault current and fault clearing time, on which the design is dependent, the inspection of the site, type of equipment and lay out will give the area covered by the station and thus the grid area. A continuous conductor laid on its peri-meter gives the configuration of the grid. When laid in parallel lines at uniform spacing gives the length of conductor. The preliminary design aims at finding suitability of grid material, conductor size, depth, layout and arrangement of conductors, conductor length for gradient control, resistance of grounding system and calculation of maximum rise of grid potential.

6.7. GRID CONDUCTOR MATERIAL:

Choice of grounding grid conductor material depends on many factors such as economics of system, type and resistivity of soil and life of grid. The cost comparison of grid materials shows that steel is the cheapest material. The graph shows that for same length cost of copper grid is nine times and of aluminium grid is three times than that of steel grid. Type and resistivity of soil helps in determining ~~the~~ roughly the corrosion of material. The low resistivity soils are more corrosive in nature than high resistive soils normally. Also steel and aluminium are more active than copper. So steel or aluminium can be recommended for high resistive soils and copper for low resistivity soils from corrosion point of view. In low resistivity soils the length of conductor is small as compared to high resistivity soils, hence the capital expenditure of grid in Rupees is also small. It will give less surface area of copper, which will result lesser corrosion of nearby steel structures.

Another factor which supports choice of any material is life of grid. If the earthing system is of a very important station, material is to be of highly resistive nature to corrosion. Otherwise for cathodic protection, extra expenditure isto be borne. Then the cost of grid will be cost of conductor plus cost for cathodic protection.

Situation of the sub-station is also given due consideration. In a remotely placed sub-station, copper may be used as it is not going to accelerate corrosion of steel structures, foundations, pipe lines etc. Details about choice of material of grid conductor have been discussed in Chapter 5.

6.8. CONDUCTOR SIZE:

After selection of the material, it is easier to select the conductor size. The conductor size is given by the formulae based on short time loading of conductor, with the assumption that all the heat is absorbed, in the material.

For copper (bolted joints)

$$A_c = I\sqrt{\frac{S}{2.87 \times 10^4}} \quad \ldots \quad \ldots (6.3)$$

For aluminium (bolted joints)

$$A_1 = I\sqrt{\frac{S}{0.789 \times 10^4}} \quad \ldots \quad \ldots (6.4)$$

For steel (bolted joints)

$$A_s = I\sqrt{\frac{S}{0.584 \times 10^4}} \quad \ldots \quad \ldots (6.5)$$

where A_c, A_1, A_s are the areas of conductor in mm^2 corresponding to material.

I is fault current in Amps.

S is the maximum time in seconds for which the fault current is passing through the grid.

But from mechanical strength point of view 4/0 i.e. 107.2mm^2, is the minimum size used for copper conductors. So the equivalent minimum size for steel and aluminium are 161mm^2 and 195 mm^2.

The last factor upon which the size of conductor depends is the corrosion of material in the soil. Due to cathodic nature of copper with respect to other metals and less chemically reactive, has got very little possibility of being corroded when buried in ground and integrity of grid will be maintained over years. But this is not the case in case of aluminium and steel. But buried in soil for even 10 years getting severely corroded in certain soils. Chemical properties of soil will help in determining this part. Cathodic protection is most useful in this respect. Even if some allowance is also given in the size of conductor, the cost of material will not be much as compared to service that it will be rendering for a number of years.

6.9. DEPTH AT WHICH CONDUCTOR IS BURIED:

Depth of the grid conductor is critical not only from the safety point, but also from the installation cost of the grid. The seasonal changes in the resistivity of soil can create hazard by changing the step voltage. The safe limit can be reached by restoring to depth to the grid conductor.

As shown by Shorotri[36], the step voltage becomes rather constant beyond two meter depth in a ground having uniform resistivity in all possible values of resistivity, while the cost of excavation goes up quite sharply. Sharotri gives from the curve, the economical depth with different resistivity values.

Soil Resistivity	Economical depth
50-100 ohm-meter	½ meter
200-400 ohm-meter	1 meter
Upto 1000 ohm meter	1.5 meter.

From the curves, for given fault duration and current, the cost of conductor material and depth of excavation can be found out readily for 100 meters length.

As the cost ofo excavation,and step and mesh voltage depends on depth and site, each case can be dealt separately.

6.10. LAYOUT AND ARRANGEMENT OF CONDUCTORS:

Inspection of layout of the equipment in the area gives idea about arrangement of conductors. A continuous conductor is to surround the area to enclose as much ground as practical. Within the grid, conductor is laid in parallel lines and preferably at reasonably uniform spacing. These lengths are laid along rows of structures or equipment to facilitate the making of ground connections. According to Thapar[9], an increase in the number of meshes beyond 64, gives practically no reduction in the resistance of a grounding grid. Therefore for having possible low resistance, the grid area is to be divided in 64 meshes and length of the conductor can be calculated, which will give most economically used conductor length.

A check over this length is made by calculating the length of conductor for gradient control and comparing this with above.

The equation for length is based on the fact that the mesh potential is to be kept within safe limits inside the grid perimeter. After choosing the economical depth, the size of conductor and spacing of parallel conductors, on which depends, the mesh potential, the length is calculated from the equation[25] given below:

$$L = \frac{K_m K_i \, PI \sqrt{t}}{165 + 0.25P_s} \quad \ldots \quad \ldots (6.6)$$

where,

L = total length of buried conductor in meters.

K_m, K_i, P_s, P.I and t are already defined in Chapter 4.

6.11. RESISTANCE OF GROUNDING SYSTEM:

Having known, the diameter of grid conductor, depth of burial, conductor length, the resistance is calculated as given in Chapter 3 by Methods 1-4. In case the grid is being laid in non-homogeneous soil, the apparent resistivity can be found as given in Chapter 2 and is used in $\overset{u}{\text{La}}$rent's equation for finding the resistance of grounding grid, which gives fairly accurate results. In case the calculated value is too high, the only way left is to extend the grid area in order to reduce the resistance

6.12. CHECK FOR CURRENT RATING OF ELECTRODES:

When the soil is loaded due to fault current, the temperature rise θ of the soil must be considered in order to avoid an over loading which might evaporate the moisture, because resistivity of soil is abruptly when moisture content rises about 22% by weight. An amount of heat $P.i^2$ is produced in every element of volume, which may be considerable because of high value of resistivity. This heat is partly stored in the volume elements of the ground which have an average specific heat $\gamma = 1.75 \times 10^6$ watt sec./$m^3 {}^\circ c$ and partly conducted from higher to lower temperature within the ground, the average heat conductivity being $\lambda = 1.2$ watt/m°c.

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Since fault currents are allowed for short time duration, thus admissible current density[13] is:

$$i = \sqrt{\frac{\gamma}{P} \cdot \frac{\theta}{t}} \qquad \ldots \qquad \ldots (6.7)$$

where,

i = current at electrode surface amp. per meter^2.

γ = specific heat in watt-sec. per m^3 degree c.

P = soil resistivity, meter-ohms.

θ = temperature rise

t = time in seconds.

As special dimensions do not appear in the equation, the relationship holds for any smooth electrode shape.

But in case of grounding grid, the flow of ground current per unit length of buried conductor is non uniform, so irregularity factor should be used. Therefore a check for the design can be made by assuming the temperature rise of soil as 80°C. Tests conducted by Armstrong, give that the specific heat is greater for low resistivity soil.

6.13. MAXIMUM GRID POTENTIAL RISE:

The determination of potential rise of substation during ground faults on the system is complicated by many factors. These include type of sub-station, location of fault, fault resistance, over-head ground and neutral wires, and tower footing resistances. The maximum potential rise is calculated on the computed grid resistance and maximum fault current, although actual can be less due to over-head, ground and neutral wires. If the calculated value is less than tolerable touch potential given by equation (4.5), the design is on the safe side, otherwise further investigation is required.

6.14. STEP VOLTAGE AT THE PERIPHERY:

Another hazard, which must be avoided is the step voltage at periphery of the grid. The grid is designed on the basis of safe step, and mesh potentials inside its periphery. So it is also necessary to consider the step potential outside. As given by Laurent and Niemann[26] the step potentials will be 0.10 to 0.15 P.i and 0.1 to 0.2 P.i., which is not the case actually.

Therefore a more reasonable approach is by using equations (4.11) and (4.13) for uniform and non-uniform soils respectively.

As given by Laurent, the external gradient near the corners of square grid can be about twice as great as at the same distance from the middle of one side in case of fine mesh, this ratio decreasing to about 1.5 as the number of meshes is decreased. According to Neimann[26] the step potential can be increased by 20 to 30 percent in case of worst conditions. Therefore it will be on the quite safe side to use 2 or higher in case of very fine mesh, the value of K_i given in equation (4.10) to get safe values of step potential.

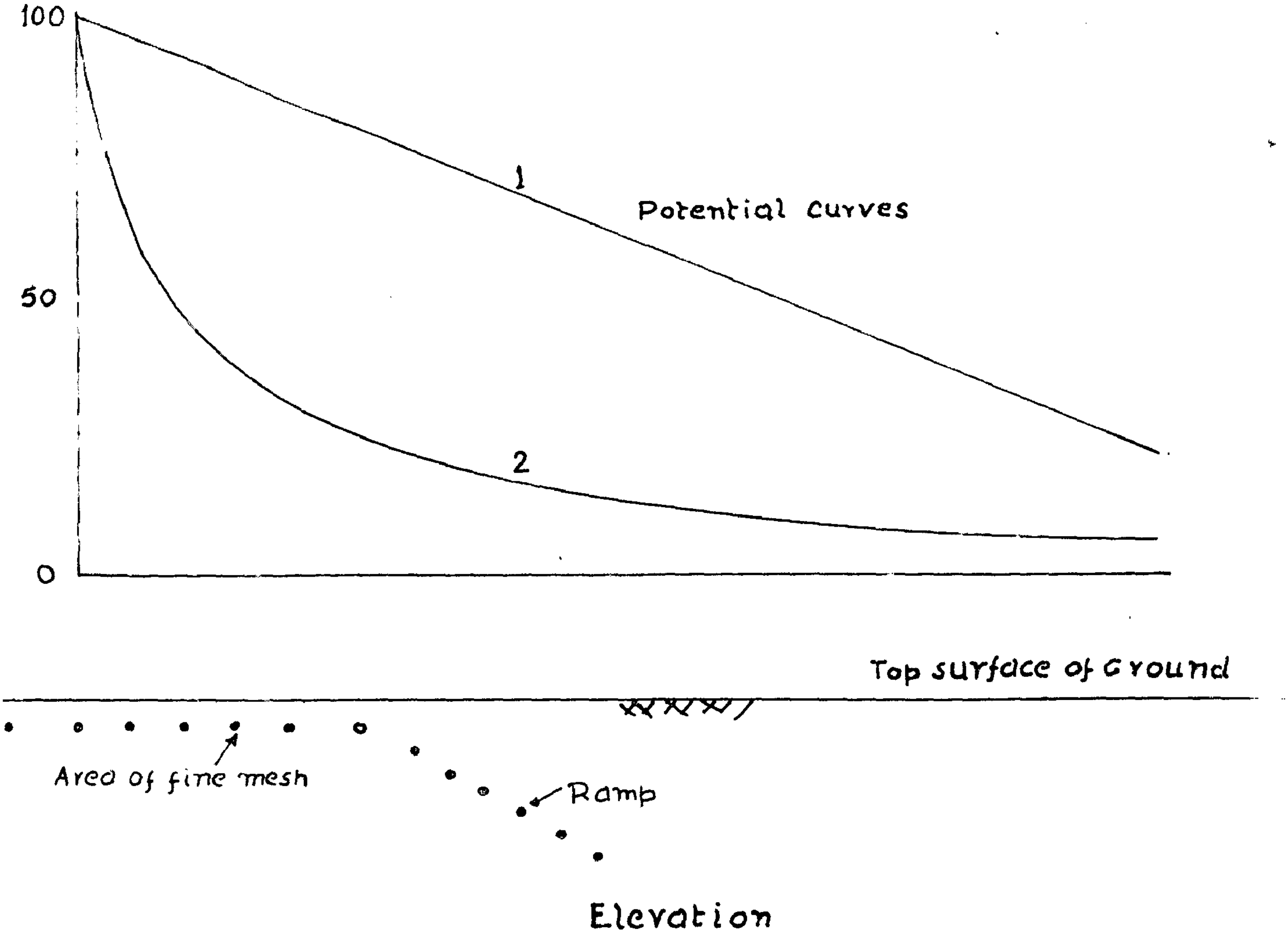
As the potential gradient is maximum just outside the periphery of grid, a crushed rock layer can be laid outside the periphery not less than 3" will be the remedy to the problem[24], because body current under most unfavourable weather and soil conditions is decreased from 50 to 90%.

According to Koch[39], the step potentials encountered at the time of fault, just outside the periphery can be 45% of total potential to ground. In order to obtain absolute safety at periphery, uniform potential, drop is obtained by so-called potential ramps. According to which, the conductor at periphery can be buried at progressively deeper depths as shown in the curve in fig.6.1.

Although the cost of conductor will rise sufficiently, this method of reducing step potential can be applied.

6.15. CALCULATION OF STEP AND TOUCH POTENTIAL INSIDE THE GRID:

When the total length of buried conductor is on the basis of gradient control given by equation (6.6), the step and



IG 6·1 POTENTIAL DISTRIBUTION IN A GROUND MAT WITH RAMP(CURVE 1) AND WITHOUT RAMP (CURVE 2)

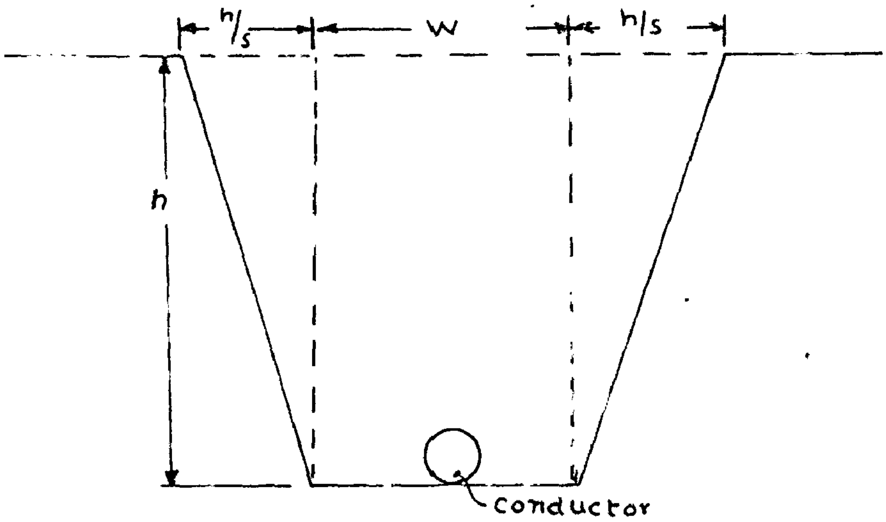


FIG 6·2 GRID CONDUCTOR IN TRENCH

touch voltages should be within tolerable limits. The check is made by equations (4.8) and (4.11). The former gives the results higher than actually exist in worst case by 10 percent and latter gives the results 8% too small, and thus can be increased.[25] If there are major irregularities existing in the geometry of grid, then more detailed investigation of all or part of station is required and a graph can be plotted.[37] These values are compared with permissible value given by equation (4.3) and (4.5). In case the voltages are higher than permissible, design can be modified.

It is necessary also to check the step and touch voltages for sustained ground currents, although these have safe values at maximum ground fault current at the apprppriate clearing time. Currents below the setting of protective relays may flow for extended periods and thus a check should be made, so that the body current is less than safe let go value i.e. 9mA.

Therefore,

$$E_{touch}(\text{sustained}) \angle (1{,}000 + 1.5\, P_s)\, \frac{9}{1000} \quad ..$$

From the expression of mesh potential it follows that-

$$\frac{K_m K_i \;\; P . I_f}{L} \angle (1{,}000 + 1.5\, P_s)\, \frac{9}{1000}$$

where,

I_f = sustained fault current

or $$I_f \angle (1000 + 1.5\, P_s)\, \frac{9}{1000} \cdot \frac{L}{K_m K_i P} \qquad .. \; (6.8)$$

Hence the sustained fault current should not be more than the above value.

6.16. TRANSFERRED POTENTIALS:

The transferred potential during a fault may cause a serious hazard between the ground grid areas and outside points. This may be of the magnitude of full value of the ground grid potential under short circuit conditions. The transfer of potential is caused by the conductors such as communication wires, rails entering the station low voltage netutral wires, conduit, metallic fences and pipes etc. In case of rails, insulating joints may be provided at the point where rails leave the ground grid area. A second set of insulating joints beyond the first,would provide against the shunting of single set by metal car or soil itself and thus avoiding hazard.

The low voltage neutral wire must be isolated from ground at station and should be treated as live wire in the station area and thus insulation, for maximum ground grid potential rise, will avoid the hazard. Water piping, gas piping and other conductors such as cable sheahhs must always be tied to the station ground system to avoid hazard within the station area. In soils of low resistivity, these potentials will not be transferred far. Where-ever necessary to stop them at grid boundary, insulating sections can be introduced.

Auxiliary buildings and employee's houses if near&when connected by water pipes, telephone to sub-station etc.,can be treated as part of sub-station and same safety criteria is applied. If more remote and conducting links are lacking, then local safety ground is required.

Special attention is required regarding the points of risk in the sub-station as given below:

6.17. OPERATING HANDLES:

When operating a handle, an arc to structure or mechanical failure or electric breakdown of insulator may occur and which can cause serious hazard and as a result of which a large percentage of fatal accidents are occuring. The safety can be achieved by providing closer mesh near the operating handle or insulated platform, metal plate form connected to handle and ground, ground loops and useof insulating handle etc.

6.18. FENCES:

In order to avoid the accessibility to general public to sub-station area and equipment, fence is most necessary. The purpose of the fence is not solved if this itself is not safe from touch potentials. Its safety is questioned, because of the highest surface gradients at the periphery of the grounding grid.

By inclusion of fence in the station area, the increase in area will reduce grid resistance substantially and thereby result in decreased maximum ground grid voltage rise. By placing the conductor outside the fence, there will result decrease in touch potential than if the fence is above the conductor. On the small station, this some times creates hazard outside which can be avoided by putting crushed rock strip along outside the fence.[24]

The other possibility is the placement of fence outside the ground grid area, either with or without close electric coupling between fence and the adjacent earth along its length, but with no electric tie between fence and main station grid.

There is danger of falling of conductor on the fence and making it unsafe. But the possibility is little due to dead end and short spans. The fence can attain dangerous potentials due to passing points of unequal potentials. Also there is no assurance of its complete isolation from grid. These hazards can be avoided by providing ten feet wide strips of crushed rock along inside of fence and keeping all metal connected to station ground at least five feet away[24].

6.19. CORRECTION OR REFINEMENT OF PRELIMINARY DESIGN:

After checking the preliminary design, if it is found that the dangerous potential differences can exist within the station, the following modification may make the design safe and thus can be applied where-ever necessary.

(i) Decrease in maximum transferred potential:

The decrease in maximum transferred potential can be achieved by decrease in total grid resistance, which will result in the lessening of maximum ground grid potential rise and hence decreased maximum transferred potential. The most effective method is by increasing the area occupied by grid. When limitation of area is there, the addition of deep driven rods may serve the purpose to some extent, but will result in increased cost of grid.

(ii) Improvement of gradient control:

The condition of a plate can be approabhed by employing closer spacing of grid conductors, which will eliminate the dangerous potentials within the station, but will result again in the increased cost of grid. The potential gradient at the grid perimeter, in case of small station with high earth resistivity is large and can create a hazard. As touch potential is more dangerous, the only method to avoid this is by burying grid perimeter ground conductor outside. The fence line which will insure that the steeper gradients immediately outside the grid perimeter do not contribute to more dangerous touch contacts. Another method is to bury two or more parallel conductors around the perimeter at successively greater depths as distance from station is increased. Again safety is achieved with increase in cost.

(iii) Decrease in step and touch potential:

Addition of high resistivity coarse crushed rock will result in increase in resistance in series with body. Body current under most unfavourable weather and soil conditions, is decreased from 50 to 90 percent by 3 to 4 inch layer of crushed rock on surface.[24] A 4 to 6 inch thickness of crushed rock decreases ratio of body to short circuit current, by ratio of 10 to 1, as compared to natural soils.[27]

(iv) Reduction of fault current:

Diverting part of fault current to other parts will reduce the total maximum potential rise of grid and potential gradients, which is possible by connecting over-head ground wires of transmission lines to the station grid. This will have effect on fault gradients near tower footing and so should be properly weighed. The grid can be made safe by limiting the short circuit current to lower values if feasible. To eliminate possibility of excessive potential differences during fault, where it is not practicable to reduce the potential gradients, is to cardon of the limited area.

The design can be made safe by using one or more of the above methods and thus suitable for construction purposes.

6.20. COST OF BURYING CONDUCTOR:

The ground system is installed after the deep excavations have been back filled and compacted and the yard has been graded, but before any surfacing is applied.

As the steel conductor size is larger as compared to equivalent copper size, it is assumed that for all depths the conductor is to be laid in trenches and back filled.

The following equation[41] gives cost per meter of, trenching, laying the conductor and back filling.

$$\text{Cost per meter} = C_1 + wkh + k/s\ h^2 \qquad .. (6.9)$$

where,

C_1 = Cost of placing the conductor in Rs./meter.

w = Width of trench bottom meters.

s = Slope of sides of trench (vertical/horizontal)

k = Cost of excavation and backfill Rs. per cubicmeter.

6.21. IMPROVEMENT OF THE GROUNDING SYSTEM BY THE USE OF CONDUCTING SALTS, COKE OR WOOD CHARCOAL:

The improvement on the conductivity of soil around earth electrode is possible by injection of electrolytes such as common salt or sodium carbonate. But due to diffusion of salts, washing away and corrosion of electrode, the treatment became absolete.

A new treatment was applied which helps in retaining the chemical in soil for a long time. The new chemicals used for this purpose are[38]:

(i) Methylenbisacrylamide (Acrylamide)

(ii) Silicate gels

(iii) Copper ferrocynide gels.

(iv) Graphite and water.

Such chemical treatment merely increases the effective dimensions of the electrodes. The first three form a gel while the fourth fills in the pours. The treatment with these gels and graphite is much more permanent than salt solutions.

Another means of improving earths surrounding the electrodes with a bed of coke, or better still with wood charcoal which are less corrosive than salts.

These conducting beds are not increasing the dimensions of the electrodes to a great extent, so that their effect on resistance is often poor. But they have the advantage of reducing seasonal variations in resistance and the same time as they increase the current that the electrode can carry without the ground being heated dangerously.

CHAPTER - 7

PRACTICAL GROUNDING GRID DESIGN

In order to judge the applicability of grounding grid design criteria, two studies are made. The two grounding grids are installed in this year by U.P. State Electricity Board at Dehradun and Roorkee 132 KV Grid sub-stations. The site of both stations is in fields having soft soil. The designs are selected, because the grids are situated at sites having homogeneous soil and non-homogeneous two layer soil respectively.

7.1. DESIGN OF GROUNDING MAT AT DEHRADUN OF 132 KV SUBSTATION:

7.1.1. Date for design:

Capacity. 12.5MVA, 132/33KV

Single line to ground fault current = 8000 Amperes.

Duration of fault current = 0.5 seconds.

Duration of fault current with back up protection=3secs.

Area of mat = 95 x 78.5 meter^2

7.1.2. Resistivity of soil at station site:

The resistivity measurement at various probe spacings indicates that the average resistivity of soil is 28.25 ohm-meter at 30 meter probe spacing and 36.4 ohm-meter at 2 meter probe spacing which is 22.4% higher. According to Endrenyi[7], a soil with variation upto 30% is considered as homo-geneous soil. It will be safe to use resistivity value 36.4 ohm-meter, The resistivity curve is shown in fig.7.1.

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7.1.3. Maximum ground fault current:

According to data vailable, the single line to ground fault current is 8000 amp. For calculating the conductor size,

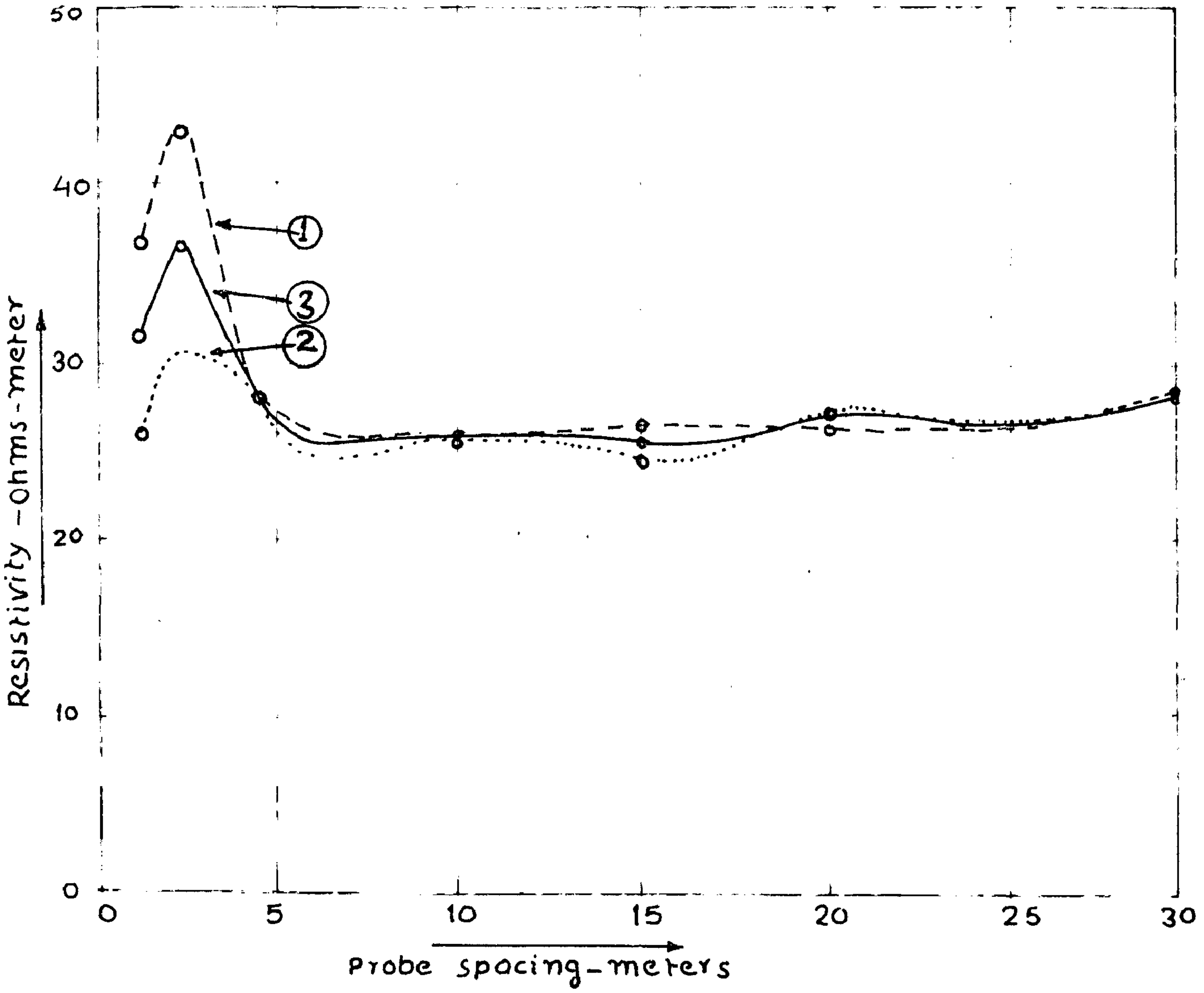


FIG 7 11. RESISTIVITY CURVE OF DEHRADUN SUBSTATION fault duration with back up protection is taken i.e. the fault clearing time of 3 seconds. The corresponding decrement factor from 6.3 to 1.0. Assuming the correction factor for future increase of fault current as 1.5; the grid is to be designed for 8000 x 1 x 1.5 = 12000 amperes.

7.1.4. CHOICE OF MATERIAL:

Steel is most suitable material for grounding grids from economic and availability point of view and it eliminates galvanic action. The low resistivity of soil as given in 5.2, falls under severely or moderately corrosive group, Thus protection from soil corrosion is very important.

7.1.5. CONDUCTOR SIZE:

For steel conductor with bolted joints the maximum allowable temperature is 500°C. and the ambient temperature is 40°C. From equation (6.5)-

$$A_s/I = \sqrt{\frac{S}{.584 \times 10^{-4}}} \text{ mm}^2/\text{Amp.}$$

$$= \sqrt{\frac{3}{.584 \times 10^{-4}}} \text{ mm}^2/\text{Amp.}$$

$$= 2.26 \times 10^{-2} \text{ mm}^2/\text{Amp.}$$

For a fault current of 12000 amp., the conductor size is-

$$\text{Area} = 2.26 \times 10^{-2} \times 12{,}000 = 272 \text{ mm}^2.$$

Using a steel strip of 2" x ¼" i.e. 50 x 6 mm^2, gives margin for corrosion also.

The equivalent diameter of conductor $= \frac{W}{2} = 0.025$meter.

7.1.6. Depth of burial of grid conductor:

The resistivity of soil falls under the low range value. Therefore taking the depth at which conductor is buried as 0.5m.

7.1.7. Resistance of mat:

For minimum resistance with economical design, dividing the 96 x 76 m^2 area into 64 meshes. Therefore the length of conductor used:

$$L = 9(96 + 76) = 1548 \text{ meters.}$$

By Laurent's formula, resistance of mat= $\frac{P}{4R} + \frac{P}{L}$

where R = equivalent radius of mat area:

$$= \sqrt{\frac{76 \times 96}{\pi}} = 48.25 \text{ m}$$

therefore resistance = $\frac{36.5}{4 \times 48.25} + \frac{36.5}{1548}$

$$= 0.2126 \text{ ohms.}$$

By Schwarz's method-

$$R = \frac{P}{\pi L} \left(\log_e \frac{2L}{a_1} + K_1 \cdot \frac{L}{\sqrt{A}} - K_2 \right)$$

where, $a_1 = \sqrt{a \times 2z}$

$$= \sqrt{0.025 \times 0.5}$$

$$= 0.112$$

Corresponding to $\frac{L}{W} = \frac{96}{76} = 1.26$; From fig. 3.5 and 3.6

$K_1 = 1.35$ and $K_2 = 5.7$

Or $R = \frac{36.4}{\pi \times 1548} \left(\log_e \frac{2 \times 1548}{0.112} + 1.35 \cdot \frac{1548}{85.4} - 5.7 \right)$

$= 0.22$ ohms.

7.1.8. Conductor length for gradient control:

Each mesh of grounding mat is 12 x 9.5m^2 size.

Now h = 0.5m, d = 0.25m and n = 9 and using D = 12m for more conservative results.

From equation 4.9,

$$K_m = \frac{1}{2\pi} \log_e \frac{12^2}{16x.5x.025} + \frac{1}{\pi} \log_e \frac{3}{4} \cdot \frac{5}{6} \cdot \frac{7}{8} \cdot \frac{9}{10} \cdot \frac{11}{12} \cdot \frac{13}{14} \cdot \frac{15}{16}$$

Or-
$K_m = 0.75$.

The value of K_i as given by equation 4.10-

$= 0.65 + 0.172 \times 9$

$= 2.2$

Taking 0.5 seconds time for fault duration as there is very rare probability of failing of primary protection and some human being is in danger.

Length for gradient control-

$$L = \frac{K_m\ K_i\ P.\ I\ \sqrt{t}}{165 + 0.25\ P_s}$$

Using 3-4 inches crushed rock layer at surface of substation having resistivity P_s = 3000 ohm meter when wet.

Therefore,

$$L = \frac{0.75 \times 2.2 \times 36.5 \times 12{,}000 \times \sqrt{0.5}}{165 + 0.25 \times 3{,}000}$$

$$= 560\text{m}.$$

and for 3 seconds fault duration L is 1370 meter. but But the length used is 1548meter.

Therefore, the design is safe from gradient control point of view. The extra length used will provide an additional factor of safety.

7.1.9. Lower setting value of relay:

The sustained ground current should be below let go value (i.e. 9mA) of the body current.

Therefore, $K_m\ K_i\ P\ \frac{I_s}{L} < (1000 + 1.5\ P_s) \cdot \frac{9}{1000}$

or,

$$I_s < \frac{1000 + 1.5 \times 3000}{36.4} \cdot \frac{9}{1000} \cdot \frac{1548}{.75 \times 2.2}$$

$$< 1265 \text{ Amp.}$$

The ground relays clearing ground fault must be set for a minimum current of less than 1265 amps.

7.1.10. Check for step voltage:

The check for step potential outside the perimeter of grid is made as under:

From equation 4.12-

$$K_s = \frac{1}{\pi}\left\{\frac{1}{2x.5}+\frac{1}{9.5+.5}+\frac{1}{2x9.5}+\frac{1}{3x9.5}+\frac{1}{4x9.5}+\frac{1}{5x9.5}+\frac{1}{6x9.5}+\frac{1}{7x9.5}+\frac{1}{8x9.5}\right\}$$

$$= 0.407$$

$$K_i = .65 + .172 \times 9 = 6.5 + 1.548 = 2.198$$

Using value of K_i as 2.5, for more conservative results.

By equation 4.11-

$$\text{Max } E_{step} = K_s . K_i . P . \frac{I}{L}$$

$$= .407 \times 2.5 \times 36.5 \times \frac{12000}{1548}$$

$$= 286 \text{ volts.}$$

Tolerable step voltage at natural surface-

$$= \frac{165 + 36.5}{\sqrt{.5}}$$

$$= 285 \text{ volts.}$$

Therefore the grid is safe from step potential outside the periphery.

7.1.11. Check of Internal mesh and step potential:

From equation 4.5 and 4.8 respectively,

$$\text{Tolerable } E_{touch} = \frac{165 + .25\, P_s}{\sqrt{t}}$$

= 1290 volts for .5 seconds fault duration

= 527 volts for 3 seconds fault duration.

$$\text{Max. } E_{mesh} = K_m\, K_i\, P\, \frac{I}{L}$$

$$= .75 \times 2.2 \times 36.5 \times \frac{12000}{1548}$$

$$= 465 \text{ volts.}$$

Therefore sufficient margin is left for the adjustment of mesh conductors for laying in the sub-station according to equipment placement.

$$\text{Tolerable } E_{step} = \frac{165 + P_s}{/t}$$

$$= 4480 \text{ volts.}$$

But Max.E_{step} in grid area is 286 volts, which is a safe value.

7.1.12. Transfer potential:

Total potential rise of station grid,

$$= 12000 \times .22$$

$$= 2640 \text{ Volts.}$$

This can result in a serious hazard during a fault as the transferred potential can be upto 2640 volts. So it is necessary to provide proper insulation to neutral wires, conduit pipes, rails and communication circuit etc.

Fence- Fence in this case is provided within the ground grid, two meters inside the boundary and earthed at 10meters interval with the grid; as a minimum distance of 5 metersis existing between extreme equipment and the fence.

7.1.13. Check of design for seasonal variation of surface resistivity:

The tolerable step and mesh potentials in the substation grounding mat are 4480V and 1290 volts and the tolerable step potential outside the perimeter of grid is 285 volts. The design gives the maximum step and mesh potentials as 286 volts and 402 volts. Even if the surface resistivity value raises due to seasonal variation, still the design is quite safe. For outside the perimeter, although both the tolerable and maximum step potentials will rise, but the rise in maximum step potential will be greater. Thus crushed rock one meter outside the perimeter is also laid.

The resistance of grounding grid as computed is 0.220 ohms which is quite a small value. Due to the large size of grid, the change in surface resistivity is not going to affect it much. Therefore there is no need of grounding rods.

7.1.14. Check for the most economical depth:

In order to check the most economical depth, it is necessary to study the variation of step and mesh potentials with depth and cost of installing the conductor (cost of laying; cost of excavation and filling) with depth.

The grid is having 64 meshes with a conductor length of 1548 meters and conductor size of 50 x 6 mm^2. The calculations show the variation of step and mesh potentials with depth, given below:

Depth-meters	.25	.5	1	1.5	2.0	3.0
Max.step potential	452V	286V	154V	120V	102V	84.6V
Max.mesh potential	532V	466V	396V	356V	319V	289V

The cost of installing the conductor is as given under:

The width of trench at bottom is 0.40meter

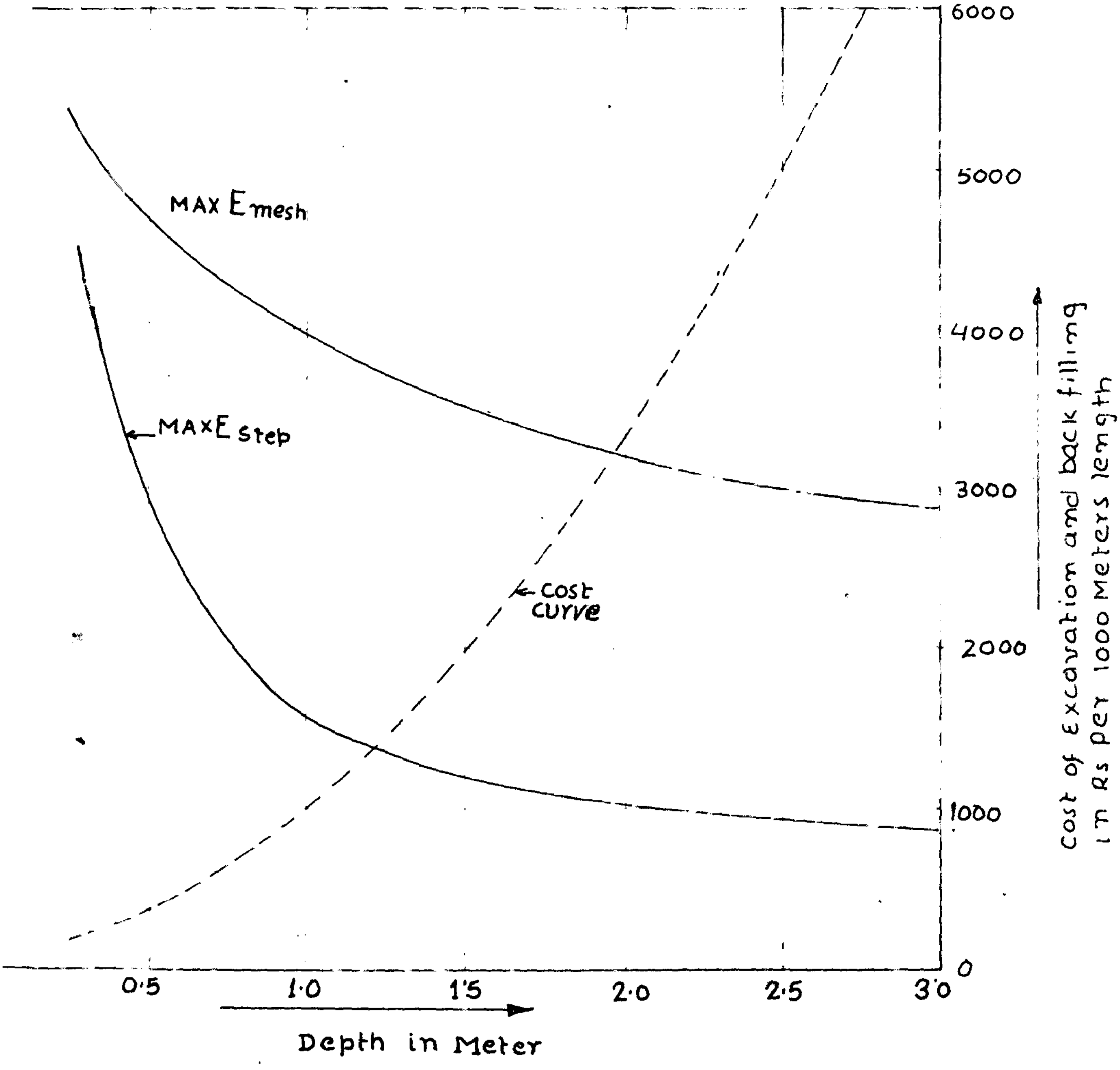
and allowable slope of soil with vertical = 30°

The cost of excavation and backfilling upto

1.525m depth .. = Rs.30 per 1000 cu.ft.
or = Rs.1062 per 1000 cub.meter.

depth beyond 1.525m = Rs. 33.50 per 1000 cub.ft.
or = Rs.1186 per 1000 cub.meter.

	With Crushed rock surface	Without crushed rock layer
tolerable E mesh	1290 V	246 V
tolerable E step	4480 V	285 V



7.1.2 VARIATION OF Max E mesh, E step and Cost OF LAYING THE CONDUCTOR WITH DEPTH

The cost of excavation and back-filling with various depths is given as under:

Depth-meters	.25	.5	1	1.5	1.525	2	3
Cost-Rs.per 1000 meters	145	336	1040	2020	2080	3340	7025

The curves given in fig. 7.2 show that E_{mesh} and E_{step} decrease with depth where as cost of installation rise with depth.

The tolerable step potential of 286V outside the grid perimeter (over natural surface) fixes the depth of burial 0.5m in order to have the minimum excavation and back filling cost.

7.1.15. Comparison of installed and designed grounding grids:

The designed grid is compared with the installed grid in various aspects such as resistance, potential differences (mesh and step potentials), life of grid and finally the cost of grid.

Resistance: The installed grid is of 95x78.5sq.m size with total length of conductor 1965 meters and 145 nos.,3m long and 3.2 dia meter grounding rods.

By Schwarz's method; the resistance of installed grid is calculated as under:

$$R_{11} = \frac{P}{\pi L} \left(\log_e \frac{2L}{a_1} + K_1 \frac{L}{\sqrt{A}} - K_2 \right)$$

where, $a_1 = \sqrt{a \text{ x} 2z} = \sqrt{.025 \text{ x } .5} = .112$

Corresponding to $\frac{L}{W} = \frac{95}{78.5} = 1.21$,

The values of K_1 and K_2 are 1.37 & 5.7 from fig.3.4 and 3.5 respectively.

$$\text{or } R_{11} = \frac{36.5}{\pi \text{x } 1965} \left(\log_e \frac{2 \text{ x}1965}{.112} + 1.37 \frac{1965}{95\text{x}78.5} - 5.7\right)$$

$$= 0.2125 \text{ ohms.}$$

$$R_{22} = \frac{P}{2\pi n L_1} \left\{ \log_e \frac{4L_1}{b} - 1 + \frac{2K_1 L_1}{\sqrt{A}} (\sqrt{n} - 1)^2 \right\}$$

$$= \frac{36.5}{2\pi\text{x}145 \text{ x}3} \left\{ \log_e \frac{4\text{x}300}{1.6} - 1 + \frac{1.37 \text{ x}2\text{x}3}{86.4} (\sqrt{145} - 1)^2 \right\}$$

$$\simeq 0.243 \text{ ohms}$$

$$R_{12} = \frac{P}{\pi L} \left(\log_e \frac{2L}{L_1} + K_1 \frac{L}{\sqrt{A}} - K_2 + 1\right)$$

$$= \frac{36.5}{\pi\text{x}1965} \left(\log_e \frac{2\text{x}1965}{3} + 1.37 \frac{1965}{96.4} - 5.7 + 1\right)$$

$$= 0.199 \text{ ohms}$$

$$\text{Now } R = \frac{R_{11} R_{22} - R_{12}^2}{R_{11} + R_{22} - 2R_{12}} = \frac{.2125 \text{ x } .243 - (.199)^2}{.2125 + .243 - 2 \text{ x } .199} = 0.2085 \text{ohms}$$

Resistance of the designed grid = 0.2195 ohms.

Therefore percentage increase in resistance = $\frac{.2195 - .2085}{.2085} . 100$

= 5.26% which is quite a small value.

Potential differences: For the installed grid, the maximum size of mesh is 13.5 x 12m.

The max. E_{mesh} for the installed grid = $K_m K_i P \frac{I}{L}$

$$\text{where } K_m = \frac{1}{2\pi} \log_e \frac{13.5^2}{16 \text{ x } .5 \text{ x} .025} + \frac{1}{\pi} \log_e \frac{3}{4} . \frac{5}{6} . \frac{7}{8} . \frac{9}{10} . \frac{11}{12} . \frac{13}{14} . \frac{15}{16} . \frac{17}{18}$$

for n=10

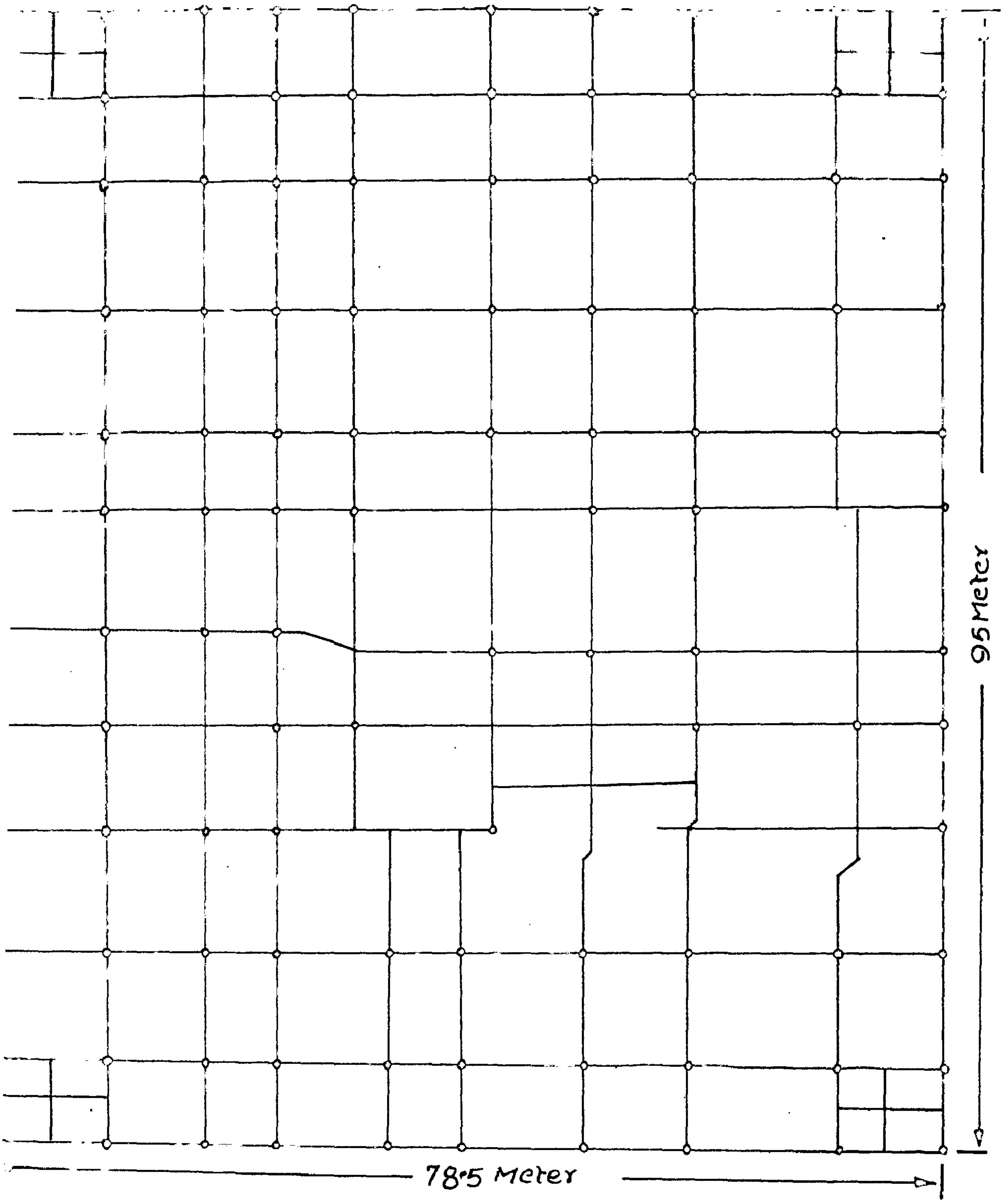
$$\text{or } K_m = 0.76$$

$$K_i = 0.65 + .172 \text{ x } 10 = 2.37$$

$$\text{Therefore Max.}E_{mesh} = .76 \text{ x } 2.37 \text{ x } 36.5 \text{ x } \frac{12000}{1965}$$

$$= 402\text{V.}$$

Max.E_{mesh} of designed grid = 465 volts.



conductor length = 1965 Meter 145 rods, 3.2 Cm dia and 300 Cm long

FIG 71.3 INSTALLED GROUNDING MAT OF 132 K.V. SUBSTATION AT DEHRADUN

Tolerable E_{mesh} = 1290V for fault duration .5 sec.

= 527V for fault duration 3 sec.

Therefore E_{mesh} of installed and designed grid are safe potentials.

Max. E_{step} for installed grid = $K_s K_i \, P \frac{I}{L}$

$$\text{where, } K_s = \frac{1}{\pi}\left(\frac{1}{2x.5} + \frac{1}{12+.5} + \frac{1}{2x12} + \frac{1}{3x12} + \frac{1}{4x12} + \frac{1}{5x12} + \frac{1}{6x12} + \frac{1}{7x12} + \frac{1}{8x12} + \frac{1}{9x12} + \frac{1}{10x12} + \frac{1}{11x12}\right)$$

= .394

taking,
K_i = 2.5

Therefore Max.E_{step} of installed grid = $.394 \times 2.5 \times 36.4 \times \frac{12000}{1965}$

= 226 volts.

Max.E_{step} of designed grid = 286 volts.

Tolerable E_{step} = 4480V for .5 sec. duration
(crushed rock surface)
= 1825V for 3 sec. duration.

Outside the gri-d boundary E_{step} = 285 volts.
(wihtout crushed rock surface)

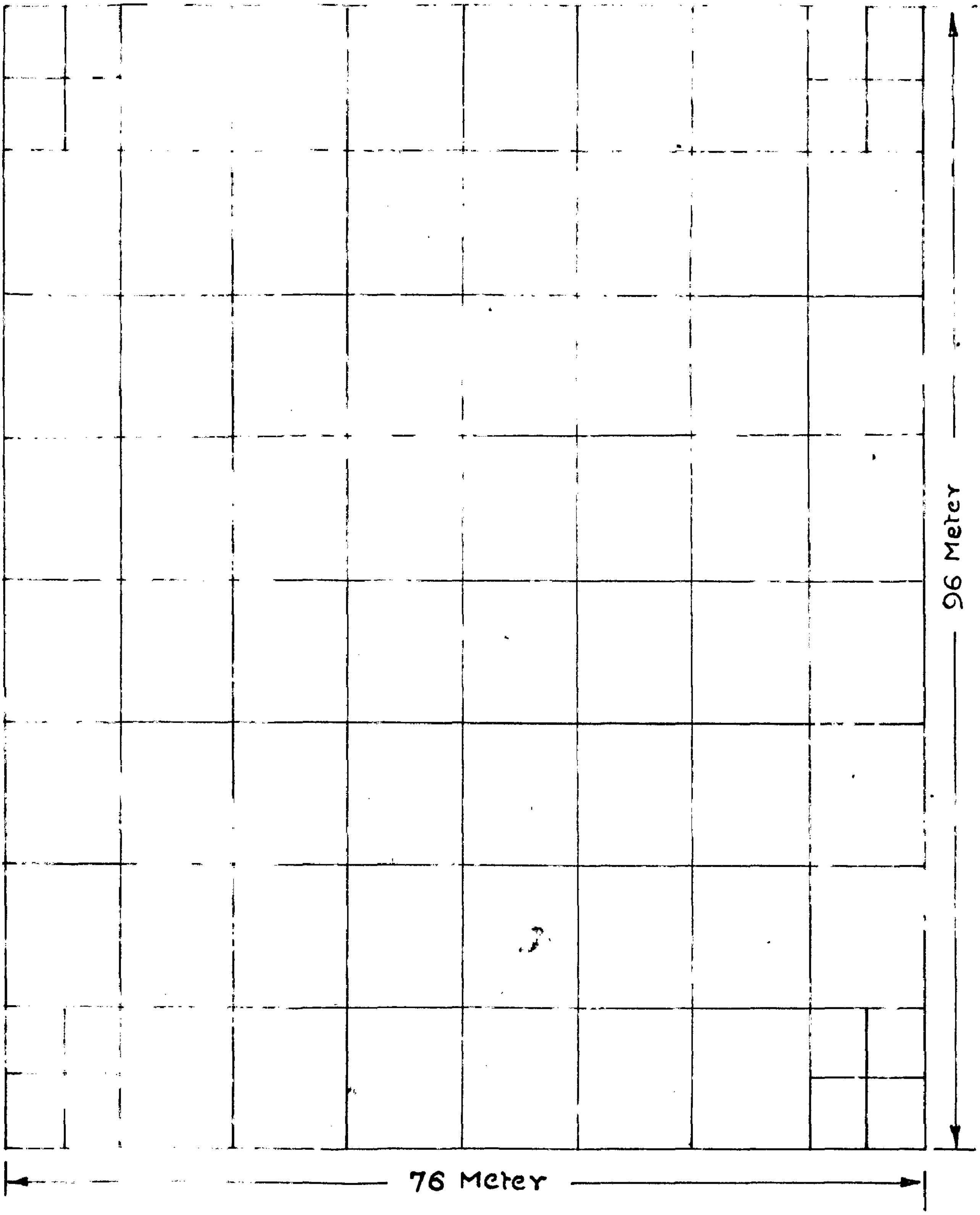
Therefore designed and installed grids are safe from Max.E_{step}.

Life of grid: The grid is installed in soil having organic matter and low resistivity and thus falls under the most corrosive group. It is very important to protect the grid from corrosion as it is a grid sub-station and when steel is used as grid material. The cathodic protection is only alternative where long life is desired. The guarantee for the designed grid is for 50 years where for the installed grid it is open to the corrosion.

Cost of installing the grid:

For the installed grid: The total length of buried conductor

= 1965 + 3 x 145 = 2400 meters.



Total length of conductor = 1634 meter

IG- 7.14 Designed Grounding Grid of Dehra Dun Substation

(Assuming cost of burying conductor and rod per meter is the same).

Therefore the excavation and refilling cost = Rs. $\frac{336 \times 2400}{1000}$

= Rs. 806.

Cost of steel conductor = Rs. $1965 \times \frac{50 \times 6}{100} \times 100 \times \frac{7.86}{1000} \times 1.2$

= Rs. 5560

Cost of galvanized steel pipe Rs.1.20 per ft.

= $145 \times 3 \times 3.28 \times 1.2$ =

= Rs.1712.

Therefore the total cost of installation of grid -

= Rs. 8078.

Cost of designed grid:

Length of conductor to be buried = 1548m.

Cost of excavation and refilling = Rs. $336 \frac{1548}{1000}$

= Rs. 520.

Cost of conductor = Rs. $1548 \frac{50 \times 6}{100} \times 100 \times \frac{7.86}{1000} \times 1.2$

= Rs. 4370.

Cost of protection of grid conductor from corrosion:

Weight of scrap iron required for 50 years = 4570 kg.
(as calculated from Appendix 3).

Taking cost of scrap iron as 30% cost of steel -

Therefore the cost of scrap iron = Rs. 1640.

Cost of rectifiers; 10% cost of steel = Rs. 556.

Expenses for power consumption for 50 years = Rs.1150.

Therefore cost of protection = Rs.3350

Therefore cost of installing the designed grid and cathodic protection = Rs. 8720.

Hence the percentage saving in cost of the installed grid

$= \frac{8720 - 8078}{8078} \times 100$

= 8%. (Approx.)

The designed grid gives the computed value of resistance 5.26% higher than installed grid computed value. The grid is safe from maximum mesh and step potentials inside and outside the boundary of grid. The saving in the cost of designed grid is 45.9% (without cathodic protection). Since the grid is situated in low resistivity soil and high corrosivity is expected, cathodic protection is a necessity. The cost of the designed grid increases by 8% than installed grid cost with a guarantee for 50 years against corrosion.

7.2. DESIGN OF GROUNDING MAT OF 132 KV ROORKEE SUB-STATION:

7.2.1. Data for Design:

Clearing time of fault = 0.5 sec.

Clearing time of fault with back-up protection = 3.0 sec.

Area of Mat = 147.5 x 66 sq.m.

Single phase to ground fault current = 8500 Amps.

7.2.2. Resistivity of Soil at Station site:

The measurement of resistivity at different probe spacings was taken at four different locations. It indicates that the earth strata in the site area consists of two layers. The resistivity of upper layer is 138.2 ohm-meter and lower layer is 47 ohm-meter.

$$\text{Reflection co-efficient } u = \frac{P_2 - P_1}{P_2 + P_1} = \frac{47 - 138.2}{47 + 138.2}$$

$$= -0.492$$

From equation 2.9,

$$P = P_2 - (P_2 - P_1)\, e^{-bs}\, (2 - e^{-bs})$$

the value of b as suited to curve is 0.45.

Corresponding to $P_1/P_2 = \frac{135.2}{47} = 2.94$, the value of δ as given in 3.19 is 1.5.

$$\text{Now } b = \frac{\delta}{2d}$$

$$\text{Therefore thickness of upper layer} = \frac{2x\ 0.45}{1.5} = 1.667\text{m.}$$

7.2.3. Maximum Ground fault Current:

According to data available, the single line to ground fault current is 8500 Amps. For fault clearing time of .5 seconds, or more, the decrement factor is 1. Assuming factor for future growth as 1.5. Hence grid is to be designed for 8500x 1 x 1.5= 12750 Amps.

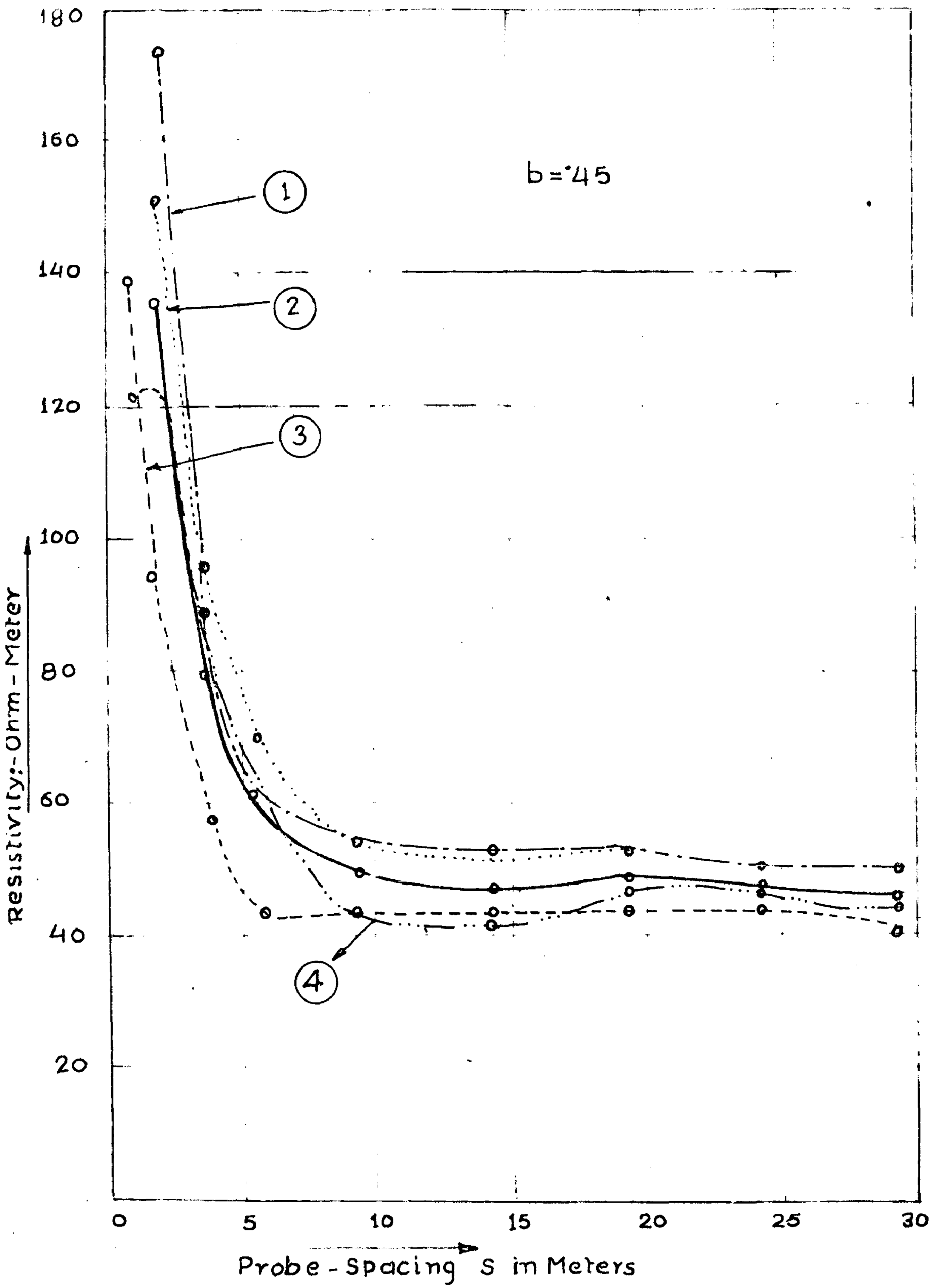


FIG 7·2·1 Resistivity Curve of Roorkee substation

7.2.4. Choice of Material:

As given in Chapter 5, the most suitable material for grid from economic and availability point of view is steel. The resistivity of soil as given in 5.2, falls under slightly corrosive group. Cathodic protection against corrosion is suggested. The cost of grid will still be much less as compared to copper grid.

7.2.5. Conductor size:

For steel conductor with bolted joints, Maximum allowable temperature = 500°C.

Taking ambient temp. = 40°C

The eqn. 6.5 gives- $A_s/I = \sqrt{\frac{S}{.584 \times 10^{-4}}}$ mm^2/Amp.

Taking the fault duration (with back-up protection) for conductor size, as 3 seconds.

Therefore cross-section of steel conductor,

$$= \sqrt{\frac{3}{.584 \times 10^{-4}}} \times 12750 \text{ mm}^2$$

$$= 288 \text{ mm}^2.$$

Choosing conductor section of 2" x ¼" or 50 x 6mm^2

Equivalent diameter of grid conductor = $\frac{W}{2}$ = 0.025m.

7.2.6. Depth of burial of Grid Conductor :

As the resistivity of soil falls within the lower range, according to Sharotri,[36] the economical depth for this resistivity range is between 0.5 meter to 1 meter.

Selecting depth of 0.5 meter for design.

7.2.7. Conductor Length:

To have the maximum use of conductor length, the mat is designed for meshes close to 64 number, because beyond which the decrease in resistance will be too small to be appreciable.

Taking the mat, to be consisting of 60 meshes, with each mesh size- 14.75 x 11 m^2.

Length of conductor used = 11 x 66 + 7 x 147.5

= 1760 meters approximately.

7.2.8. Resistance of Grid:

For non-uniform soil, the apparent resistivity of soil is found as under:

The value of P_a corresponding to-

Area = $9735 m^2$

b = 0.45

No. of meshes = 60

$L/W = \frac{147.5}{66} = 2.235$

Conductor radius (Equivalent) = 1.25 cm.

therefore is $\frac{P_a - P_1}{P_2 - P_1} = .75$

or apparent resistivity $= P_1 + (P_2 - P_1)\ .75$

= 70 ohm-meter.

Equivalent radius of grid area $= \sqrt{9735/\pi} = 55.6$meters

By Laurent's formula-

$$R = \frac{70}{4 \times 55.6} + \frac{70}{1760} = 0.356 \text{ ohms}$$

By Schwarz's formula-

$$R = \frac{P}{\pi L} \left(\log_e \frac{2L}{a_1} + K_1 \times \frac{L}{\sqrt{A}} - K_2 \right)$$

where, $a_1 = \sqrt{\frac{.0125}{2} \times 2 \times .5}$

$= 0.112$

Corresponding to $L/W = 2.235$, $K_1 = 1.31$ and $K_2 = 5.9$.

$$R = \frac{70}{\pi \times 1760} \left(\log_e \frac{2 \times 1760}{.112} + 1.31 \times \frac{1760}{98.6} - 5.9\right)$$

$$= 0.352 \text{ ohms}$$

7.2.9. Check for Maximum Step Voltage:

To check the maximum step voltage outside the grid periphery for n = 7 and D = 11 meter, from eqn. 4.13-

$$\text{Max.}E_{step} = \frac{135.2 \times 12750}{\pi \times 1760} \left\{ \sum_{k=1}^{n} \left\{ \log_e \frac{(K-1)11+1}{(k-1)11+.0125} + \sum_{m=1}^{\infty} (-.492)^m \log_e \frac{\{(k-1)11+1\}^2+(2m \times .5)^2}{\{(k-1)11+.0125\}^2+(2m \times .5)^2} \right\} \right\}$$

$$= 312 \left\{ \log_e \frac{1}{.0125} \cdot \frac{12}{11} \cdot \frac{23}{22} \cdot \frac{34}{33} \cdot \frac{45}{44} \cdot \frac{56}{55} \cdot \frac{67}{66} \cdot + (-.492)^m \right.$$

$$\sum_{m=1}^{\infty} (-.492)^m \log_e \frac{1+m^2}{m^2} \cdot \frac{12^2+m^2}{11^2+m^2} \cdot \frac{23^2+m^2}{22^2+m^2} \cdot \frac{34^2+m^2}{33^2+m^2} +$$

$$\left. \frac{45^2+m^2}{44^2+m^2} \cdot \frac{56^2+m^2}{54^2+m^2} \cdot \frac{67^2+m^2}{66^2+m^2} \right\}$$

$$= 1305 \text{ volts.}$$

For n = 11 and D = 14.75meters

$$\text{Max. } E_{step} = \frac{135.2 \times 12750}{\pi \times 1760} \left\{ \sum_{k=1}^{n} \left\{ \log_e \frac{(k-1)14.75+1}{(k-1)14.75+.0125} + \sum_{m=1}^{\infty} (-.492)^m \log_e \frac{\{(k-1)14.75+1\}^2+m^2}{\{(k-1)14.75+.0125\}^2+m^2} \right\} \right\}$$

$$= 1292 \text{ Volts.}$$

But Tolerable step voltage = $\frac{165 + \rho_s}{\sqrt{.5}}$

= 428Volts for natural soil surface

Therefore the area outside the grid is unsafe from dangerous step potential.

Laying crushed rock layer of 3 to 4" thick 2 meter wide outside the periphery having resistivity 3000 ohm-meters, when wet,

$$\text{Tolerable } E_{step} = \frac{165 + 3000}{\sqrt{.5}} = 4480 \text{ Volts}$$

7.2.10. Check for Internal Mesh Potentials:& Step potential :

Now Max. E_{mesh} as given by eqn. 4.14

$$= \frac{135.2 \times 12750}{\pi \times 1760} \left\{ \sum_{k=1}^{n} \right\} \frac{1}{2} \log_e \frac{\{(k-1)11 - 11/2\}^2 + r^2}{\{(k-1)11 + .0125\}^2 + r^2} +$$

$$\sum_{m=1}^{\infty} (-.492)^m \log_e \frac{\{(k-1)11 - 11/2\}^2 + m^2}{\{(k-1)11 + .0125\}^2 + m^2} \Bigg\} \Bigg\}$$

or

$\text{Max.}E_{mesh} = 1222$ Volts.

But Tolerable E_{mesh} corresponding to the .5 seconds fault duration and crushed rock layer $= \dfrac{165 + .25\, P_s}{\sqrt{t}}$

$= 1282$ Volts

Therefore the grounding mat is safe from mesh potential.

The maximum step potential is 1305 volts in the grid area, but the tolerable step voltage is 4480 volts with crushed rock surface layer, which means the mat is safe from step potential also.

7.2.11. Transferred Potential:

Total potential rise of station grounding mat

$= 12750 \times .352 = 4480$ volts., which is more than the tolerable touch potential and can result in a serious hazard during a fault. It is necessary to provide proper insulation to neutral wires, conduit pipes, rails communication circuit and control cables etc.

A metallic fence is provided within the ground grid 1½meter inside the perimeter and connected at regular intervals throughout its length.

7.2.12. Check for Lower setting value of Relay :

The sustained shock current should be below 'let go value' i.e. 9 mA. of body current.

Therefore,

$$K_m \, K_i \, P \, \frac{I_s}{L} \text{ should be less than } (1000 + 1.5P_s)\frac{9}{1000}$$

$$\text{Equivalent value of } K_m = \frac{\text{Max. } E_{mesh}}{K_i \, P. \, \frac{I}{L}}$$

$$= \frac{1222 \times 1760}{2.5 \times 138.2 \times 12750} = .486$$

$$\therefore \text{ or } I_s \text{ is less than } (1000 + 1.5 \times 3000)\frac{9}{1000} \cdot \frac{L}{(K_m K_i P)}$$

$$\angle\, 5.5 \times 9 \times \frac{1760}{.486 \times 2.5 \times 138.2}$$

$$\angle\, 520 \text{ Amps.}$$

The ground relays clearing ground fault must be set for a minimum current of less than 520 Amps.

7.2.13. Comparison of installed and designed ground grid:

The comparison is taken in different aspects such as resistance, potential differences (mesh and step potentials), and the cost of grid.

Resistance: The installed grid is of 147.5 x 66m^2 size having

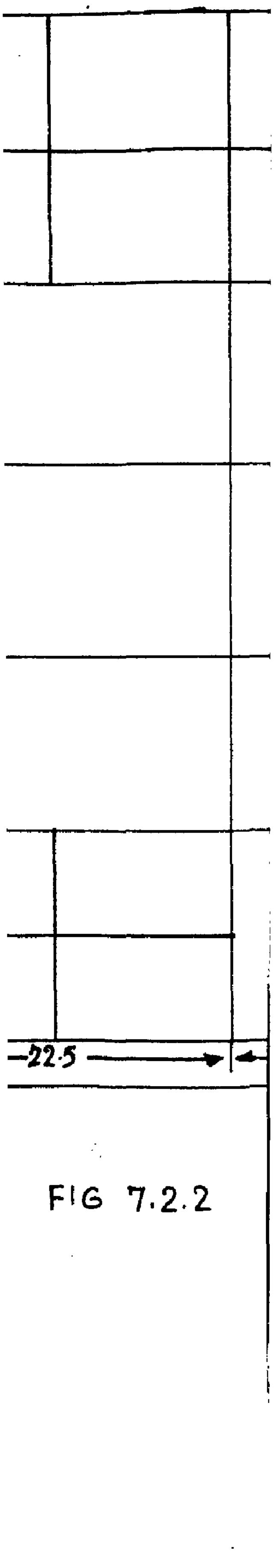


FIG 7.2.2

used 1600 m conductor of 56 x 6 mm^2 size and 36 rods 3 m long and 3.2 cm. dia meter.

Apparent Resistivity of soil as calculated is 70 ohm-meter.

By Schwarz's method, the resistance of installed grid is calculated as under:

$$R_{11} = \frac{P}{\pi L} \left(\log_e \frac{2L}{a_1} + K_1 \frac{L}{\sqrt{A}} - K_2 \right)$$

where $a_1 = \sqrt{0.028 \times .5}$ $\qquad \sqrt{A} = \sqrt{147.5 \times 66}$

$= 0.1185 \qquad = 98.6m.$

According to $\frac{L}{W} = \frac{147.5}{66} = 2.24$, $K_1 = 1.31$ and $K_2 = 5.9$

$$\text{or } R_{11} = \frac{70}{\pi \times 1600} \left(\log_e \frac{2\times1600}{.1185} + 1.31 \times \frac{1600}{98.6} - 5.9 \right)$$

$= 0.356$ ohms.

$$R_{22} = \frac{70}{2\pi \times 36 \times 3} \left\{ \log_e \frac{4\times300}{1.6} - 1 + \frac{2\times1.31\times3}{98.6} (\sqrt{36}-1)^2 \right\}$$

$= 0.784$

$$R_{12} = \frac{70}{\pi \times 1600} \left(\log_e \frac{1600 \times 2}{3} + 1.31 \times \frac{1600}{98.6} - 5.9 + 1 \right)$$

$= 0.325$

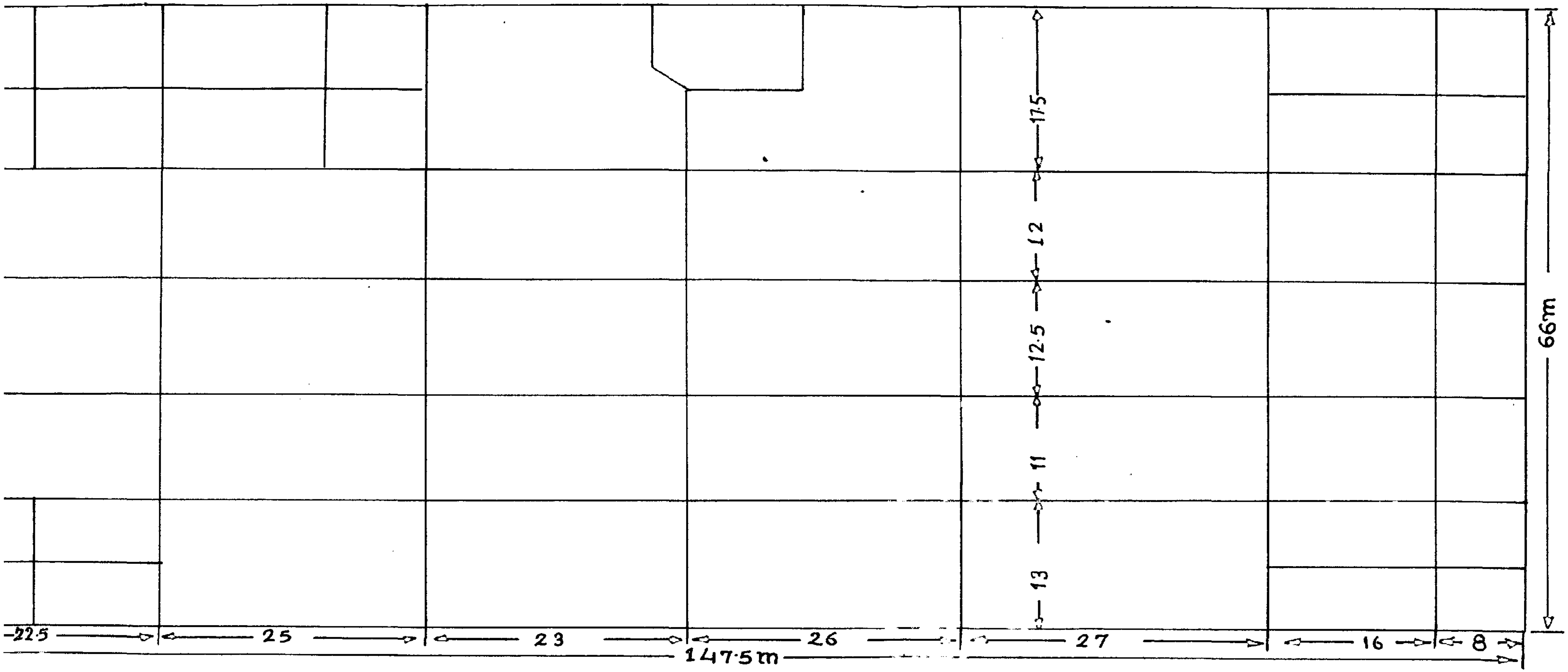
$$\text{Now } R = \frac{R_{11} \cdot R_{22} - R_{12}^2}{R_{11} + R_{22} - 2R_{12}} = \frac{.356 \times .784 - (.325)^2}{.356 + .784 - 2 \times .325}$$

$= 0.353$ ohms

Resistance of the designed grid = 0.352 ohms

Therefore percentage decrease in resistance $= \frac{.353 - .352}{.353} \times 100$

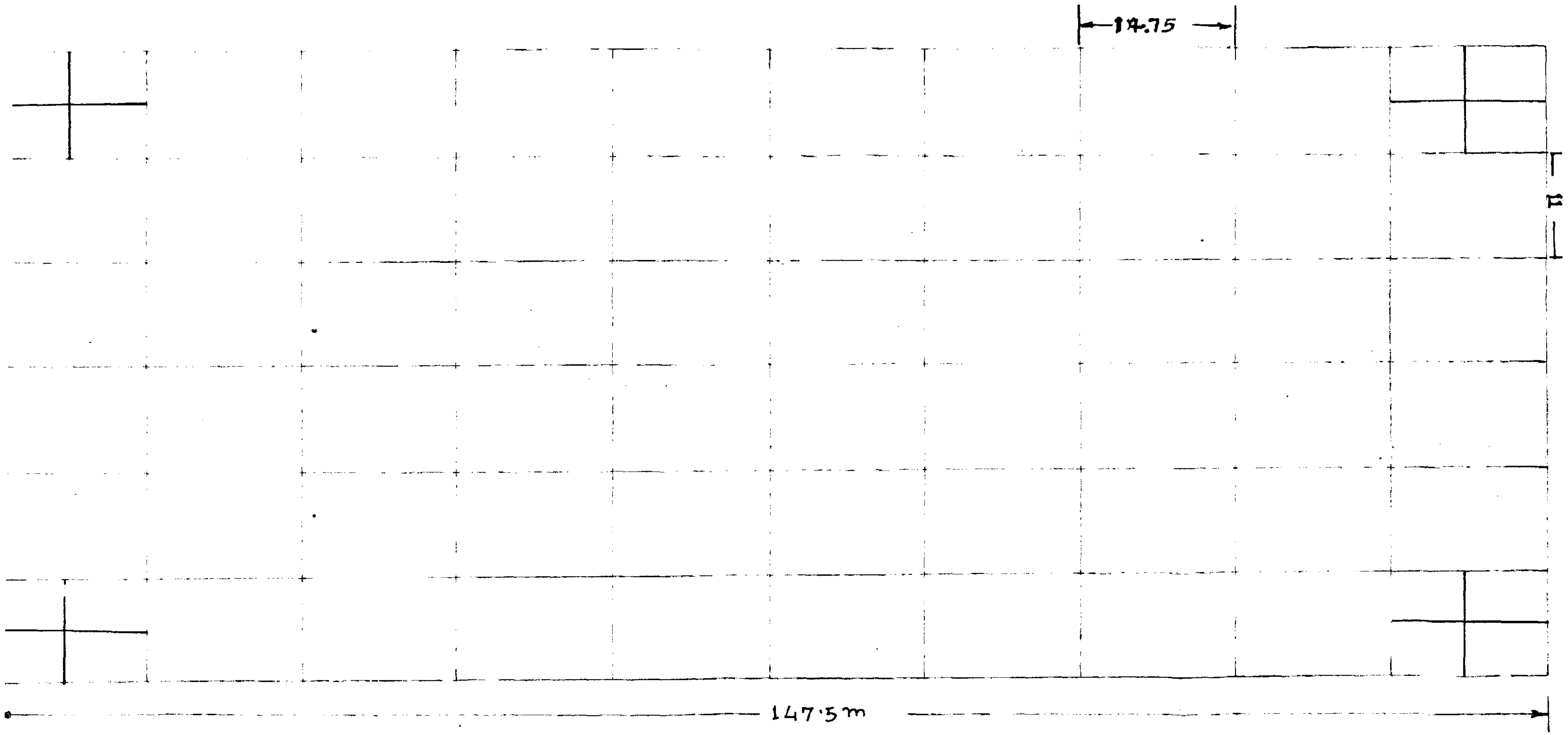
$= 0.3\%$.



LENGTH OF CONDUCTOR USED= 1600 m, 36 rods, 3.2 cm DIA and 300cm long.

[SCALE 1M=0.5cm]

FIG 7.2.2 INSTALLED GROUNDING GRID AT ROORKEE OF 132 KV SUB STATION.



TOTAL LENGTH OF CONDUCTOR = 1760 Meters

FIG 7.2.3 Designed Grounding Grid of Roorkee substation

Potential Differences:

The maximum E_{mesh} for the installed grid, according to Thapar's equation 4.14-

$$\text{Max.}E_{mesh} = \frac{135.2 \text{x} 12750}{\pi \text{x} 1600} \left\{ \sum_{K=1}^{8} \left\{ \tfrac{1}{2}\log_e \frac{\{(K-1)27.5-13.75\}^2+.014^2}{\{(K-1)27.5+.014\}^2+.014^2} + \sum_{m=1}^{\infty} (-.492)^m \log_e \frac{\{(K-1)27.5-13.75\}^2+m^2}{\{(K-1)27.5+.014\}^2+m^2} \right\} \right\}$$

$= 1318$ Volts

Max.E_{mesh} for the designed grid $= 1222$ volts

Tolerable E_{mesh} for 0.5 sec. fault duration

with crushed rock layer at surface $= 1282$ Volts.

The Maximum E_{mesh} of the installed grid indicated that the mesh potential is unsafe even with a crushed rock layer at the surface, thus the installed grid fails in design. The designed grid is safe from mesh potential.

Max. E_{step} for the installed grid $= \dfrac{135.2 \text{ x } 12750}{\pi \text{ x } 1600}$.

$$\left\{ \log_e \frac{1}{.014} \cdot \frac{9}{8} \cdot \frac{25}{24} \cdot \frac{52}{51} \cdot \frac{78}{77} \cdot \frac{101}{100} \cdot \frac{126}{125} \cdot \frac{148.5}{147.5} - .492\log 2.445 + .242 \log 1.48 - .1194 \log 1.275 + .0586 \log 1.18 + \ldots \right\}$$

$= 1410$ Volts.

Max. E_{step} for designed grid $= 1305$ volts.

Tolerable E_{step} for .5 sec. duration of fault current

with crushed rock layer $= \dfrac{165 + 3000}{\sqrt{.5}} = 4480$ volts.

Tolerable E_{step} for 0.5 sec. duration of fault current

just outside the boundary $= \dfrac{165 + 141.5}{\sqrt{.5}} = 428$ volts which indicates that a crushed rock layer is required outside the perimeter to make it safe from maximum step potential.

Life of Grid:

The resistivity curve analysis gives that the soil is having two layers, of which the upper layer is of 1.667meter thickness and having resistivity 141.5 ohm-meters and the sub-soil resistivity is 47 ohm-meter, and the location is in the fields. The grid is installed in upper layer at a depth of 0.5m. The table in Chapter 5 indicates that this upper layer soil is having slightly corrosive soil properties. The cathodic protection will certainly help in avoiding corrosion, but it is not at all a must. The use of galvanized steel can avoid corrosion for a minimum period of 10 years.

Cost of the Grid:

For the installed Grid:

The total length of conductor used = 1600m

Cost of conductor = $1600 \times \frac{56 \times 6}{100} \times 100 \times \frac{7.86}{1000} \times 1.2$

= Rs. 5060.

Cost of rods = Rs. 36 x3x3.28 x1.2 = Rs. 425.

Cost of excavation & refilling for 1960m = Rs.$336 \times \frac{1960}{1000}$

=Rs.660.

(Assuming cost of burying conductor and rods per meter is the same)

Total cost = Rs.6145.

For the designed grid:

Cost of conductor = Rs. $1760 \times \frac{50 \times 6}{100} \times 100 \times \frac{7.86}{1000} \times 1.2$

= Rs. 4980.

Cost of excavation and refilling =Rs.$336 \times \frac{1760}{1000}$ =Rs.590.

Total cost without cathodic protection = Rs.5570.

Percentage saving in grid cost = $\frac{6145 - 5570}{6145}$

= 9.35%.

Cost of protection of grid conductor from corrosion:

Weight of scrap iron required for 50 years as calculated in Appendix 3 = 10.88A Kg. where A is surface area of grid conductor

$= 1088 \times 1760 \times \frac{112}{1000}$ kg.

= 2142 Kg.

Assuming price of scrap iron 30% of regular price of steel,

Therefore cost of scrap iron = Rs. .3x2142x1.2 = Rs.772.

Cost of rectifiers (assumed as 10% cost of steel) =Rs.500.

Cost of power consumption for 50 years =

$= \text{Rs. } 35.7 \times 10^{-3} \times \left(\frac{1760 \times 112}{1000}\right)^2$

= Rs. 1388.

Total cost of protection = Rs. 772 + Rs.500 + Rs.1388

= Rs. 2660.

Total cost of designed grid with cathodic protection

= Rs. 8230.

Percentage increase in cost = $\frac{8230 - 6145}{6145} = \frac{2085}{6145}$

= 34%.

The designed grid gives the computed value of resistance nearly equal to installed grid value. The installed grid is unsafe from mesh potential even with crushed rock layer surface of substation area. The designed grid is safe from internal mesh and step potentials, but just outside the boundary of grid crushed rock layer for some distance say 2 meters is necessary to keep it safe from dangerous step potential. The saving in the cost of designed grid (without cathodic protection) is 9.35%, but the cost is more by 34% with cathodic protection giving a guarantee for the life of grid for 50 years.

CONCLUSION.

1. The resistivity curve (the relation between the measured resistivity using the 4-probe method and the spacing of probes) in different seasons of the year is necessary for the design of a grounding system, as it helps in computing the resistance and potential gradients correctly and thus directly affects the economy.

2. Soil analysis can help in finding corrosivity of soil, which in turn affects the size of conductor and cathodic protection and thus the cost of protection. It can also help in the choice of grounding material.

3. Cost of an iron grid with cathodic protection in most corrosion soils is 25% of the cost of copper grid while the cost of aluminium grid with cathodic protection can be equal to the cost of copper grid. Thus from economic point of view the choice of material for a grid is iron, aluminium and copper in order of increasing cost. From the point of economy, all earth conductors should be of steel.

4. A surface layer of crushed rock greatly reduces the potential gradients in the substation area resulting in the reduction of conductor length and thus the cost of grid.

5. In the preliminary design of grounding grids the number of meshes must be taken as about 64 in order to attain most economical results.

6. Maximum fault current, mechanical strength, and corrosion considerations determine the size of the conductor.

7. The choice regarding the depth of burial of grounding grid conductor is made from the step potential, mesh potential and cost of laying of conductor and each design must be considered on its own merits.

APPENDIX - I

CONDUCTOR SIZE & COST COMPARISON FOR DIFFERENT MATERIALS:

Assuming that the heat loss during the short time of flow of fault current through grid conductor is neglected. The equation determining short time current carrying capacity of conductor is as under:

Rate of chage of temperature $\frac{d\theta}{dt} = \{ I^2 \frac{P_o}{A} . L(1+\alpha\theta)0.23885 \times \frac{1}{LA\delta} . \frac{1}{s}$

where I is the fault current

A is cross-section of conductor

δ density of conductor material

s is specific heat of conductor material

t is fault duration

P_o is specific resistance of conductor material

or

$$\frac{d\theta}{dt} = (\frac{I}{A})^2 \times .23885 \frac{P_o}{\delta s} \times (1 + \alpha\theta)$$

$$\frac{d\theta}{1+\alpha\theta} = (\frac{I}{A})^2 \times \frac{0.23885}{\delta . s} . P_o dt$$

Integrating both sides,

$$\frac{1}{\alpha} \{ \log_e (1+\alpha\theta) + \beta \} = (\frac{I}{A})^2 \times \frac{0.23885}{\delta . s} . P_o . t$$

when t = 0 seconds, $\theta = \theta_a$

or $\beta = - \log_e (1 + \alpha\theta_a)$

Therefore $\frac{1}{\alpha} \log_e \frac{1+\alpha\theta}{1+\alpha\theta_a} = (\frac{I}{A})^2 \times \frac{0.23885}{\delta . s} . P_o . t$

or $\frac{I}{A} = \sqrt{9.66 . \frac{\delta . s}{\alpha P_o t} \log_{10} \frac{1+\alpha\theta}{1+\alpha\theta_a}}$

For copper-

$P_o = 1.589 \times 10^{-6}$ ohm-centimeter.

$\alpha = .00427$

$\delta = 8.92$ gm/cc.

$s = .092$ cal/gm°C.

Taking ambient temperature $\theta_a = 40°C$

<u>For bolted joints:</u> The maximum allowable temperature $\theta = 250°C$

Therefore cross-sectional area of conductor, $a = I\sqrt{\frac{t}{2.87 \times 10^4}}$

where a is in mm^2 and t is in seconds.

<u>For brazed joints:</u> The maximum allowable temperature $\theta = 450°C$

Therefore cross-sectional area of conductor, $a\ mm^2 = I\sqrt{\frac{t}{4.65 \times 10^4}}\ mm^2$

<u>Aluminium:</u>

$P_o = 2.607 \times 10^{-6}$ ohm-centimeter.

$\alpha = 0.0039$

$\delta = 2.7$ gm/cm^3

$s = .223$ cal./gm°C.

<u>For bolted joints:</u> The maximum allowable temperature = 150°C

Therefore cross-sectional area $a\ mm^2 = I\sqrt{\frac{t}{.789 \times 10^4}}$

<u>For brazed joints:</u> The maximum allowable temperature = 270°C

Therefore the cross-sectional area of conductor $a\ mm^2 = I\sqrt{\frac{t}{1.43 \times 10^4}}$

<u>Steel:</u>

$P_o = 15 \times 10^{-6}$ ohms-centimeter.

$\alpha = .00423$

$\delta = 7.86$ gm./cc.

$s = 0.114$ cal./gm.°C.

<u>For bolted joints:</u> The allowable maximum temperature is 500°C

Therefore the cross-sectional area $a\ mm^2 = I\sqrt{\frac{t}{.584 \times 10^4}}$

For brazed joints:

The maximum allowable temperature is 900°C.

Therefore the cross-sectional area of conductor a mm^2

$$= I\sqrt{\frac{t}{0.841 \times 10^4}}$$

ased on the above formulae, the Minimum Conductor Sizes for various
current
ault durations are given below:

Cross-sectional area in mm^2 per ampere.

ime uration f Fault n econds	Bolted joints			Brazed joints		
	Copper	Aluminium	Steel	Copper	Aluminium	Steel
30	3.22×10^{-2}	6.16×10^{-2}	7.16×10^{-2}	2.54×10^{-2}	4.58×10^{-2}	5.96×10^{-2}
4	1.18 "	2.25 "	2.62 "	0.928 "	1.67 "	2.18 "
1	0.59 "	1.125 "	1.31 "	0.463 "	0.836 "	1.09 "
0.5	0.416"	0.795 "	0.924"	0.328 "	0.591 "	0.77 "

Cost of conductor material:

Copper @ Rs. 2220/kg. Cost = @.(a/100).100.1000.(δ/1000).100

Aluminium @ Rs. 12/kg. = @. a . δ .100

Steel @ Rs. 1.2/kg.

Fault duration	Cost/100 meter length /1000 Amps. fault current in Rupees					
	Copper	Aluminium	Steel	Copper	Aluminium	Steel
	Bolted joints			brazed joints		
30 sec.	638	200	67.6	504	148.20	56.30
4 sec.	238	72.8	24.7	184	54.10	20.56
1 sec.	119	36.4	12.4	91.6	27.05	10.28
.5 sec.	82.5	26.75	8.72	65	19.15	7.26

Without cathodic protection & minimum size considerations, copper grid is 3.4 times costier than Aluminium grid and 9.6 times costier than steel grid.

APPENDIX - 2

MEASUREMENT OF RESISTIVITY.

The measurement of resistivity of soil was taken with 'Megger' Earth Tester, Null Balance type. This was done by inserting four electrodes into ground at equal intervals A. The depth of insertion of electrodes should not exceed 1/20th of "A". Due to very shallow depth of insertion of electrodes, they are likely to have exceptionally high resistances, for this test therefore the guard terminal 'G' should generally be used and connected to a fifth electrode inserted midway between P_2 and C_2 electrodes.

Resistivity Measurement at Dehradun- The measurement of resistivity at Dehra Dun sub-station site was taken at three different locations with various probe spacings in different directions as given in the table below:

obe Spac-ig in ters	Resistance in ohms			Resistivity in ohm-meters			Average
	Site I	Site II	Site III	Site I	Site II	SiteIII	
1	5.77	4.13	3.95	36.25	25.95	31.10	31.10
2	3.39	2.42	2.90	42.5	30.40	36.40	36.40
4	1.13	1.12	1.125	28.40	28.15	28.25	28.30
6	0.68	0.66	0.67	25.65	24.85	25.20	25.25
10	0.41	0.41	0.41	25.75	25.75	25.75	25.75
15	0.28	0.26	0.27	26.40	24.50	25.45	25.45
20	0.21	0.22	0.215	26.40	27.65	27.00	27.00
25	0.17	0.17	0.17	26.50	26.50	26.50	26.50
30	0.15	0.15	0.15	28.25	28.25	28.25	28.25

Since the difference between the maximum and minimum average resistivity value is less than 20% the soil is taken as homogeneous soil. For more conservative results the higher resistivity value is to

Resistivity Measurement at Roorkee:- The measurement of resistivity at Roorkee sub-station site was taken at four different locations with probe spacings from one meter to 30 meter in different directions as given in the table below:

obe acing ters.	Resistance in ohms				Resistivity in ohm-meters				
	Site I	Site II	Site III	Site IV	Site I	Site II	Site III	Site IV	Average
1	-	-	22.0	19.4	-	-	138.2	122.0	130.1
2	13.8	12.0	7.43	9.9	173.5	150.9	93.4	123.0	135.2
4	3.34	3.67	2.23	3.36	83.9	92.3	56.1	84.5	79.2
6	1.6	1.83	1.12	1.69	60.4	69.0	42.2	63.6	58.8
10	0.86	0.85	0.69	0.68	54.0	53.4	43.4	42.6	48.35
15	0.56	0.54	0.46	0.44	52.8	50.9	43.4	41.5	47.15
20	0.42	0.42	0.35	0.37	52.8	52.8	44.00	46.5	49.0
25	0.32	0.32	0.28	0.30	50.2	50.9	44.0	47.1	48.0
30	0.27	0.27	0.22	0.24	50.9	50.9	41.4	45.2	47.1

APPENDIX - 3

COST OF SCRAP IRON REQUIRED AND POWER CONSUMPTION FOR CATHODIC PROTECTION.

The weight of an element deposited at an electrode is proportional to quantity of electricity which has passed.

$$w = B\left(\frac{a}{v}\right) It$$

where,

w = weight of deposit in grammes.

I = current in amperes.

t = time in seconds.

a = atomic weight.

v = valency

B = constant, equal to the number of grammes of hydrogen deposited by the passage of electricity 1 Coulomb, is 0.00001038 g/c.

Therefore for iron (v = 2),

Electro chemical equivalent = $B\left(\frac{a}{v}\right) = 0.2890$mg./Coulomb.

Weight of iron deposited =0.2890 It mg.

Taking purity of scrap iron 90%, weight of metal taken away from anode $= \frac{0.2890\ It}{0.9}$ mg.

$$= \frac{0.2890 A.\delta.t}{0.9} \text{ mg.}$$

where, A is the area of metal surface to be protected in square meters, and δ is current density 2 to 3 mA/ft^2. or 21.46 mA to 32.19mA per meter^2.

or weight $= \frac{.2890}{.9} \cdot 10.73 \left(\frac{2 \text{ to } 3}{1000}\right)$A.t mg.

For 50 years minimum weight of metal required to be buried

$$= \frac{.2890}{.9} \times 10.73 \times \left(\frac{2 \text{ to } 3}{1000}\right) . \frac{50.365.24.3600}{1000.1000} \text{ .A.Kg.}$$

$$= 10.89 \text{ A to } 16.32 \text{ A Kg.}$$

Assuming cost of scrap iron to be 30% of cost of steel used. Therefore cost of scrap iron used for 50 years-

$$= \text{Rs. } 0.3 \times 1.2\ (10.89 \text{ to } 16.32)A = \text{Rs. } (3.92 \text{ to } 5.89)\ A.$$

Cost of Power Consumption: Current density usually required for the cathodic protection of steel structure is 2 to 3 mA./ft.^{2} or 21.46 to 32.19mA per meter.^{2}

Therefore, power consumption for 50 years-

$$= \left[\frac{(21.46A \text{ to } 32.19A)}{1000}\right]^2 \times .\frac{59 \times 50 \times 365 \times 24}{1000} \text{ Kwh.}$$

or cost of power consumption-

$$= \text{Rs. } 0.3 \times \frac{(21.46 \text{ to } 32.29)^2}{1000 \times 1000} \times 0.59 \frac{50 \times 365 \times 24}{1000} A^2$$

$$= \text{Rs. } (35.7 \text{ to } 80.8) \times 10^{-3} \times A^2.$$

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