

14. Design of Grounding System

14.1 Design Criteria. As stated in 2.1, there are two main design goals to be achieved by any substation ground system under normal as well as fault conditions. These are (1) to provide means to dissipate electric currents into the earth without exceeding any operating and equipment limits, and (2) to assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

The design procedures described in the following sections are aimed at achieving safety from dangerous step and touch voltages within a substation. It is pointed out in 6.1 that it is possible for transferred potentials to exceed the GPR of the substation during fault conditions. Section 15 discusses some of the methods used to protect personnel and equipment from these transferred potentials. Thus, the design procedure described here is based on assuring safety from dangerous step and touch voltages within, and immediately outside, the substation fenced area. Since the mesh voltage is the worst possible touch voltage inside the substation (excluding transferred potentials), the mesh voltage will be used as the basis of this design procedure. Since the mesh voltage is the worst possible touch voltage (excluding transferred potentials), the mesh voltage will be used as the basis of this design procedure.

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Step voltages are inherently less dangerous than mesh voltages. If, however, safety within the grounded area is achieved with the assistance of a high resistivity surface layer (crushed rock), which does not extend outside the fence, then step voltages may be dangerous. In any event, the computed step voltages should be compared with the permissible step voltage after a grid has been designed that satisfies the touch voltage criterion.

¿ mesh voltage = touch voltage ?

For equally spaced ground grids, the mesh voltage will increase along meshes from the center to the corner of the grid. The rate of this increase will depend on the size of the grid, number and location of ground rods, spacing of parallel conductors, diameter and depth of the conductors, and the resistivity profile of the soil. In a computer study of three typical grounding grids in uniform soil resistivity, the data shown in Table 7 were obtained. These grids were all symmetrically shaped square grids with no ground rods and equal parallel conductor spacing. The corner E_m was computed at the center of the corner mesh. The actual worst case E_m occurs slightly off-center (toward the corner of the grid), but is only slightly higher than the E_m at the center of the mesh.

As indicated in Table 7, the corner mesh voltage is generally much higher than that in the center mesh. This will be true unless the grid is unsymmetrical (that is, has projections, or is L-shaped, etc), has ground rods located on or near the perimeter, or has extremely nonuniform conductor spacings. Thus, in the simpli-

Table 7
Typical Ratio of Corner-to-Center Mesh Voltage

Grid Number	Grid Size (Meshes · Meshes)	E_m Corner/Center
1	10 · 10	2.71
2	20 · 20	5.55
3	30 · 30	8.85

fied equations for the mesh voltage E_m given in 14.5, only the mesh voltage at the center of the corner mesh is used as the basis of the design procedure.²⁷ Analysis based on computer programs, described on 14.9, may use this approximate corner mesh voltage, the actual corner mesh voltage, or the actual worst-case touch voltage found anywhere within the grounded area as the basis of the design procedure. In either case, the initial criterion for a safe design is to limit the computed mesh or touch voltage to below the tolerable touch voltage from Eq 26 or 26a.

E_m : mesh voltage at the center of the corner mesh.

includes son los cc. 26 y 26a?

14.2 Critical Parameters. The following site-dependent parameters have been found to have substantial impact on the grid design: maximum grid current (I_G), fault duration (t_f), shock duration (t_s), soil resistivity (ρ), high resistivity surface material (ρ_s), and grid geometry. Several parameters define the geometry of the grid, but the area of the grounding system, the conductor spacing, and the depth of the ground grid have the most impact on the mesh voltage, while parameters such as the conductor diameter and the thickness of the surfacing material have less impact [B1], [B33], [B36], [B97]. A brief discussion or review of the critical parameters is given below.

14.2.1 Maximum Grid Current (I_G). The evaluation of the maximum design value of ground fault current that flows through the substation grounding grid into the earth, I_G , has been described in Section 13. In determining the maximum current I_G , by means of Eq 54, consideration should be given to the resistance of the ground grid, division of the ground fault current between the alternate return paths and the grid, the decrement factor, and the future expansion of the power system.

I_G : maximum grid current.

14.2.2 Fault Duration (t_f) and Shock Duration (t_s). The fault duration and shock duration are normally assumed equal, unless the fault duration is the sum of successive shocks, such as from reclosures (Section 13). The selection of t_f should reflect fast clearing time for transmission substations and slow clearing times for distribution and industrial substations. The choices t_f and t_s should result in the most pessimistic combination of fault current decrement factor and allowable body current. Typical values for t_f and t_s range from 0.25 - 1.0 s. Sections 3.2-4.3 and 13.4 give more detailed information on the selection of t_f and t_s .

14.2.3 Soil Resistivity (ρ). The grid resistance and the voltage gradients within a substation are directly dependent on the soil resistivity. Since in reality

²⁷ Unless otherwise specified, the remainder of the guide will use the term mesh voltage (E_m) to mean the touch voltage at the center of the corner mesh.

E_m : the touch o' mesh voltage?

soil resistivity will vary horizontally as well as vertically, sufficient data must be gathered for a substation yard. Section 11.3 describes the widely used Wenner technique to measure the soil resistivity [B110], [B71].

Since the simplified equations for E_m and E_s given in 14.5 assume uniform resistivity soil, the equations can employ only a single value for the resistivity. There is no simple method to determine a value from the field test data that can yield an accurate ground grid analysis using these simplified equations. However, the following points may provide the user with general guidelines.

(1) The soil can be considered uniform if the difference between two extreme resistivity values of the field test data is 30% or less. In this case a simple average of all the resistivity values can be used in Eqs 70 and 73. *ecuaciones para E_m y E_s .*

(2) When an equivalent two-layer soil model is determined (see 11.5.2) and the ground system is in the upper layer, the value of ρ_1 (upper-layer soil resistivity) can be used in the simplified equations. As stated in 11.5.2, for negative values of reflection factor K , the grids designed using uniform soil analysis will have higher step and touch voltages than the grids designed with the equivalent two-layer model, if ρ_1 is used as the soil resistivity in Eqs 70 and 73.

14.2.4 Resistivity of Surface Layer (ρ_s). A thin surface layer of crushed rock helps in limiting the body current by adding resistance to the equivalent body resistance. Values from 1000-5000 Ω -m have been used for ρ_s . Refer to 5.4 and '0.5 for more details on the application of this parameter.

14.2.5 Grid Geometry. In general, the limitation on the physical parameters of a ground grid are based on economics and the physical limitations of the installation of the grid. The economic limitation is obvious: it is impractical to install a copper plate grounding system. Section 16 describes some of the limitations encountered in the installation of a grid. For example, the digging of the trenches into which the conductor material is laid limits the conductor spacing to approximately 2 m or more. Typical conductor spacings range from 3-15 m, while typical grid depths range from 0.5-1.5 m. For the typical conductors ranging from AWG 2/0 to 500 kcmils, the conductor diameter has negligible effect on the mesh voltage. The area of the grounding system is the single most important geometrical factor in determining the resistances of the grid. The larger the area grounded, the lower the grid resistance and, thus, the lower the GPR and mesh voltage.

In general, the limitation on the physical parameters of a ground grid are based on economics and the physical limitation of the installation of the grid.

14.3 Index of Design Parameters. Table 8 contains a summary of the design parameters used in the design procedure.

14.4 Design Procedure. The block diagram of Fig 25 illustrates the sequences of steps to design the ground grid. The parameters shown in the block diagram are identified in the index presented in Table 8 of 14.3.

(1) The property map and general location plan of the substation should provide good estimates of the area to be grounded. A soil resistivity test, described in Section 11, will determine the soil resistivity profile and the soil model needed (that is, uniform or two-layer model).

(2) The conductor size is determined by equations given in 9.3 and 9.4. The fault current $3I_0$ should be the maximum expected future fault current that will

Table 8
Index of Design Parameters

Symbol	Description	Reference Sections
$3I_0$	Symmetrical fault current in substation for conductor sizing in A	9.3, 9.4, 13.2, 13.4
I_G	Maximum grid current that flows between ground grid and surrounding earth (including dc offset) in A	13.4
ρ	Soil resistivity in $\Omega\cdot\text{m}$	11
ρ_s	Surface layer resistivity in $\Omega\cdot\text{m}$	5.4, 10.5
h_s	Surface layer thickness	5.4
C_p	Current projection factor for future system growth	13.1, 13.10
C_s	Surface layer resistivity derating factor	5.4
t_c	Duration of fault current for sizing ground conductor in s	9.3, 9.4, 9.6
t_f	Duration of fault current for determining decrement factor in s	13.9
t_s	Duration of shock for determining allowable body current in s	3.2-4.3
h	Depth of ground grid conductors in m	12.2, 12.3
d	Diameter of grid conductor in m	9.3, 9.4, 9.6
A	Total area enclosed by ground grid in m^2	12.2, 12.3
D	Spacing between parallel conductors in m	14.4, 14.5
D_f	Decrement factor for determining I_G	13.1, 13.9, 14.2
n	Number of parallel conductors in one direction	14.4, 14.5
K_m	Spacing factor for mesh voltage, simplified method	14.4, 14.5
K_s	Spacing factor for step voltage, simplified method	14.4, 14.5
K_i	Corrected factor for grid geometry, simplified method	14.4, 14.5
K_{ii}	Corrective weighting factor that adjusts the effects of inner conductors on the corner mesh, simplified method	14.5, A
K_h	Corrective weighting factor that emphasizes the effects of grid depth, simplified method	14.5, A
L	Total length of grounding system conductor, including grid and ground rods in m	14.5
R_g	Resistance of ground system in Ω	12.1-12.4
E_m	Mesh voltage at the center of the corner mesh for simplified method in V	14.4-14.5
E_s	Step voltage between a point above the outer corner of the grid and a point 1 m diagonally outside the grid for simplified method in V	14.4-14.5
$E_{\text{touch } 50}$	Tolerable touch voltage for human with 50 kg body weight in V	6.2, 6.3
$E_{\text{touch } 70}$	Tolerable touch voltage for human with 70 kg body weight in V	6.2, 6.3
$E_{\text{step } 50}$	Tolerable step voltage for human with 50 kg body weight in V	6.2
$E_{\text{step } 70}$	Tolerable step voltage for human with 70 kg body weight in V	6.2

be conducted by any conductor in the grounding system, and the time t_f should reflect the maximum possible clearing time (including back-up).

(3) The tolerable touch and step voltages are determined by equations given in 6.2 and 6.3. The choice of time t_s is based on the judgement of the design engineer, with guidance from 3.2-4.3.

(4) The preliminary design should include a conductor loop surrounding the entire grounded area, plus adequate cross conductors to provide convenient

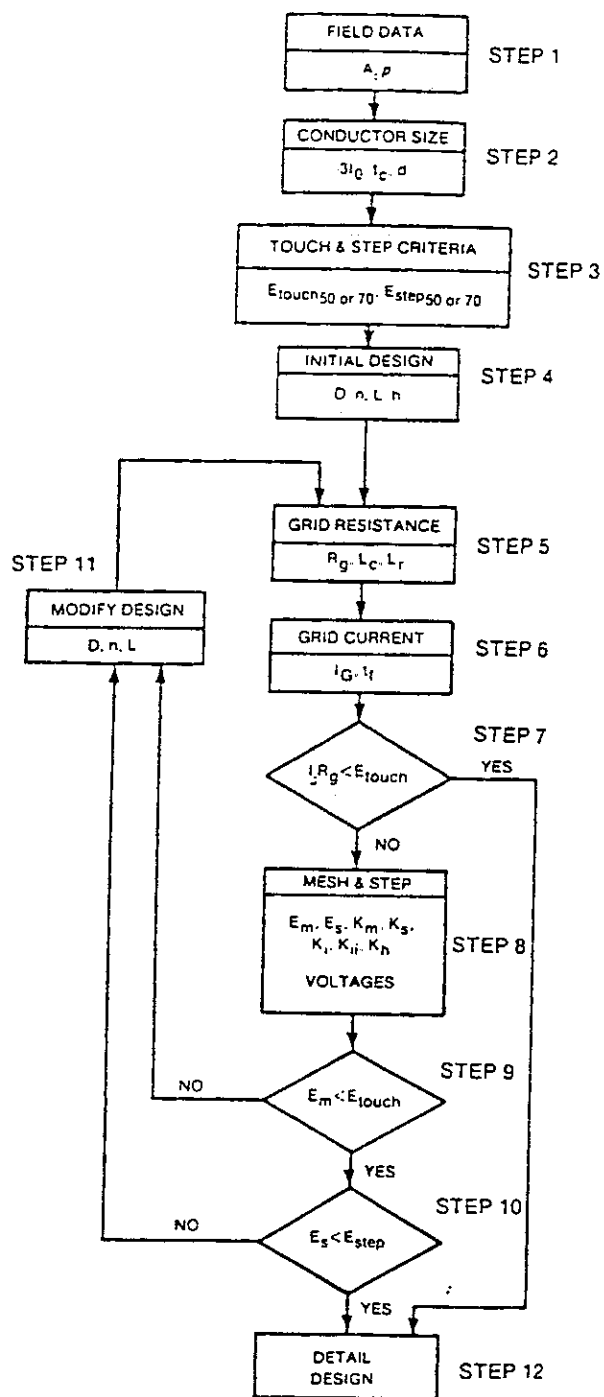


Fig 26
Design Procedure Block Diagram

access for equipment grounds, etc. The initial estimates of conductor spacing and ground rod locations should be based on the current I_G and the area being grounded.

(5) Estimates of the preliminary resistance of the grounding system can be determined by the equations given in 12.2 and 12.3.

For the final design, more accurate estimates of the resistance may be desired, especially when ground rods are used to reach more conductive subsoils. For this application, Eqs 42-44 may be utilized to include the effects of two different soil resistivities in computing the grid resistance and the rodbed resistance. Computer analysis based on modeling the components of the grounding system in detail can compute the resistance with a high degree of accuracy, assuming the soil model is chosen correctly.

(6) The current I_G is determined by the equations given in Section 13. In order to prevent gross over-design of the grounding system, only that portion of the total fault current $3I_0$ that flows through the grid to remote earth (and contributes to the mesh and step voltages and the GPR) should be used in designing the grid. The current I_G should, however, reflect the worst fault type and location, the decrement factor, and any future system expansion.

(7) If the GPR of the preliminary design is below the tolerable touch voltage, no further analysis is necessary. Only additional conductor required to provide access to equipment grounds is necessary.

(8) The calculation of the mesh and step voltages for the grid as designed can be done by the approximate analysis techniques described in 14.5, or by the more accurate computer analysis techniques, as demonstrated in 14.9. Further discussion of the calculations are reserved for those sections.

(9) If the computed mesh voltage is below the tolerable touch voltage, the design may be complete [see Step (10)]. If the computed mesh voltage is greater than the tolerable touch voltage, the preliminary design shall be revised [see Step (11)].

(10) If both the computed touch and step voltages are below the tolerable voltages, the design needs only the refinements required to provide access to equipment grounds. If not, the preliminary design must be revised [see Step (11)].

(11) If either the step or touch tolerable limits are exceeded, revision of the grid design is required. These revisions may include smaller conductor spacings, additional ground rods, etc. More discussion on the revision of the grid design to satisfy the step and touch voltage limits is given in 14.7.

(12) After satisfying the step and touch voltage requirements, additional grid conductors and ground rods may be required. The additional grid conductors may be required if the grid design does not include conductors near equipment to be grounded. Additional ground rods may be required at the base of surge arresters, transformer neutrals, etc.

14.5 Calculation of Maximum Step and Mesh Voltages. Computer algorithms for determining the grid resistance and the mesh and step voltages have been developed in numerous recent references [B2], [B35], [B52], [B57], [B61]. These algorithms required considerable storage capability and may be relatively expen-

sive to execute. In many cases, it is not economically justifiable to use these computer algorithms, or the designer may not have access to a computer with the required capabilities. This section, in conjunction with Appendix A, describes approximate equations for determining the design parameters and establishing the corresponding values of E_m and E_s without the necessity of using a computer. In addition, Appendix B provides curves for a quick estimate or rough check of the calculated values of R_g , E_m , and E_s , or both, based on plotted data, for square grids without ground rods.

Generally,

$$E_m = \rho K_m K_i I_G / L \quad (\text{Eq 66})$$

and

$$E_s = \rho K_s K_i I_G / L \quad (\text{Eq 67})$$

Thus, the mesh and step voltage values are obtained as a product of geometrical factors (K_m or K_s , respectively), a corrective factor (K_i), which accounts for the increase in current density in the grid extremities, the soil resistivity (ρ), and the average current density per unit of buried conductor (I_G/L).

While the above general Eqs 66 and 67 do not differ from the equations used in the previous editions of the guide, the specific formulas for K_m and K_s have been changed and perform differently than those used in the past. The derivations of the new formulas for K_m and K_s , along with the explanation for the differences between the old and new formulas, are included in Appendix A.

14.5.1 Mesh Voltage (E_m). In Appendix A, Sections 2-5 derive a factor K_m based on the geometry of a ground grid with no ground rods. This K_m is proportional to the mesh voltage E_m , as previously described. The relationship between K_m and E_m depends largely on the current density in the perimeter conductors versus the current density in the inner conductor. To reflect this effect of current density and to correct some of the deficiencies in the equation for K_m in past editions of this guide, the role of K_m has been re-evaluated and two additional weighing terms, K_{ii} and K_h , included in a new equation below, developed by Sverak [B100]:

$$K_m = \frac{1}{2\pi} \left[\ln \left(\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d} \right) + \frac{K_{ii}}{K_h} \ln \frac{8}{\pi(2n-1)} \right] \quad (\text{Eq 68})$$

where

$K_{ii} = 1$ for grids with ground rods along the perimeter, or for grids with ground rods in the grid corners, as well as both along the perimeter and throughout the grid area

$K_{ii} = \frac{1}{(2n)^{2/n}}$ for grids with no ground rods or grids with only a few ground rods, none located in the corners or on the perimeter

$$K_h = \sqrt{1 + h/h_o}$$

$h_o = 1$ m (reference depth of grid)

and D , h , n , and d are defined in Table 8.

As explained in Appendix A, a corrective factor K_i is needed to compensate for the fact that the subject mathematical model of N parallel conductors cannot fully account for the effects of a grid geometry, that is, for two sets of parallel conductors that are perpendicular to each other and interconnected at the cross-connection points. (K_i was originally derived as a function that, for a nonsimplified definition of K_m , shown as Eq A26 in Appendix A of this guide, matched the $K_m K_i$ product to the results of Koch's experiment with scale grid models described in Appendix A. This factor is ²⁸:

$$K_i = 0.656 + 0.172 n \quad (\text{Eq 69})$$

Now a general equation for the mesh voltage E_m can be expressed in terms of ρ , I_G , L , K_m , and K_i :

$$E_m = \frac{\rho I_G K_m K_i}{L} \quad (\text{Eq 70})$$

where K_m is determined by Eq 68 and K_i is determined by Eq 69.

If L_c represents the total grid conductor length and L_r represents the total ground rod length, then for grids with ground rods

$$E_m = \frac{\rho I_G K_m K_i}{L_c + 1.15 L_r} \quad (\text{Eq 71})$$

The 1.15 multiplier for L_r in Eq 71 reflects the fact that the current density is higher in the ground rods near the perimeter than in the grid conductors.²⁹

For grids with no ground rods, or with only a few rods located within the grid but away from the perimeter

$$E_m = \frac{\rho I_G K_m K_i}{L_c + L_r} \quad (\text{Eq 72})$$

14.5.2 Step Voltage (E_s). Section 1.7 of Appendix A derives a factor K_s based on the geometry of a ground grid with no ground rods. As with the mesh voltage, this K_s is proportional to the step voltage E_s .

$$E_s = \frac{\rho I_G K_s K_i}{L} \quad (\text{Eq 73})$$

²⁸ Previous editions of this guide defined $K_i = 0.65 + 0.172 n$. The correction of 0.65 to 0.656 reflects the obvious fact that for $n = 2$, K_i must be 1.0.

²⁹ The value of 1.15 is probably too conservative. Indications are that a multiplier of 2.0 or more may be valid for peripheral rods. However, considering that there is a lack of field data and not much information is available on practical experience with grounding systems designed using predominantly peripheral ground rods, judgement should be exercised in the use of Eqs 71 and 72. If only a few, relatively short, ground rods are placed near the center of the grid (that is, for surge arresters, control buildings, etc), the grounding system behaves very much like a grid without ground rods (Eq 72). As more ground rods are placed near the perimeter or the lengths of the ground rods are increased, or both (that is, L_r approaches L_c), the results obtained using Eq 71 become more conservative.

where

$L = L_c + L_r$ for grids with no ground rods or only a few rods in the center away from the perimeter

or

$L = L_c + 1.15L_r$ for grids with ground rods predominantly around the perimeter

For simplification, the maximum step voltage is assumed to occur at a distance equal to the grid depth, h , just outside the perimeter conductor. For the usual burial depth of $0.25 \text{ m} < h < 2.5 \text{ m}$

$$K_s = \frac{1}{\pi} \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D} (1-0.5^{n-2}) \right] \quad (\text{Eq 74})$$

and for depths smaller than 0.25 m,

$$K_s = \frac{1}{\pi} \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D} W \right] \quad (\text{Eq 75})$$

where

$$W = \frac{1}{2} + \frac{1}{3} + \frac{1}{4} \dots + \frac{1}{n-1}$$

or for $n \geq 6$

$$W \approx \frac{1}{2(n-1)} + \ln(n-1) - 0.423$$

The use of a different equation for K_s , depending on the grid depth h , reflects the fact that the step voltage decreases rapidly with increased depth.

14.6 Estimate of Minimum Buried Conductor Length. A simple equation can be developed to permit a preliminary determination of buried grid conductor necessary to keep the maximum touch voltage within the grounded area below the safe limits established by Eqs 26 and 26a of 6.2. This is done by equating Eq 67 with Eq 26 or 26a of 6.2 as shown below.

For $E_m < E_{\text{touch}50}$, combining Eqs 71 and 26 gives

$$\frac{K_m K_i \rho I_G}{L} < (1000 + 1.5 C(h, K) \rho_s) \frac{0.116}{\sqrt{t_s}} \quad (\text{Eq 76})$$

Rearranging Eq 76 for L gives

$$L > \frac{K_m K_i \rho I_G \sqrt{t_s}}{(116 + 0.174 C(h, K) \rho_s)} \quad (\text{Eq 77})$$

Similarly, for $E_m < E_{\text{touch}70}$, combining and rearranging Eqs 70 and 26 gives

$$L > \frac{K_m K_i \rho I_G \sqrt{t_s}}{(157 + 0.235 C(h, K) \rho_s)} \quad (\text{Eq 78})$$

Cases may occur where the conductor length derived from Eqs 77 and 78 is too great to be economically feasible. In such situations, some of the suggestions mentioned in 14.7 may be considered.

Where soil resistivity and total ground current are very low, the length obtained from Eqs 77 or 78 may give a total length of conductor that is too small to properly connect all equipment to be grounded. In this case, more conductor may be required, even though it is not necessary for safety reasons.

14.7 Refinement of Preliminary Design. If calculations based on the preliminary design indicate that dangerous potential differences can exist within the station, the following possible remedies should be studied and applied where appropriate.

(1) Decrease in total grid resistance will decrease the maximum ground grid potential rise and hence the maximum transferred potential. The most effective way to decrease ground grid resistance is by increasing the area occupied by the grid. Deep driven rods or wells may be used if the available area is limited. Decrease in station resistance may or may not decrease appreciably the local gradients, depending on the method used.

(2) Improvement of gradient control. By employing closer spacing of grid conductors, the condition of the continuous plate can be approached more closely. Dangerous potentials within the station can thus be eliminated at a cost. The problem at the perimeter may be more difficult, especially at a small station where earth resistivity is high. However, it is usually possible, by burying the grid perimeter ground conductor outside the fence line, to ensure that the steeper gradients immediately outside this grid perimeter do not contribute to the more dangerous touch contacts. Another effective and economical way to control perimeter gradients is to increase the density of ground rods at the perimeter. This density may be decreased toward the center of the grid. Another approach to controlling perimeter gradients and step potentials is to bury two or more parallel conductors around the perimeter at successively greater depth as distance from the station is increased [B1], [B7], [B67].

(3) Diverting a greater part of the fault current to other paths, for example, by connecting overhead ground wires of transmission lines or by decreasing the tower footing resistances in the vicinity of the substation. In connection with the latter, however, the effect on fault gradients near tower footings should be weighed.

(4) Limiting of short-circuit currents flowing in the ground mat to lower values. If feasible, this will, of course, decrease the total rise in ground mat voltage and all gradients in proportion. Other factors, however, will usually make this impractical. Moreover, if accomplished at the expense of greater fault clearing time, the danger may be increased rather than diminished.

(5) Barring of access to limited areas where it may be impractical to eliminate possibility of excessive potential differences during a fault.

By using one or more of the above methods where necessary, designs can be completed for construction purposes. These should be reasonably liberal, as

GPR = ground grid
potential rise

grounding facilities can usually be installed more cheaply if all go in as part of the general construction job, without the necessity of making additions later.

14.8 Limitations of Simplified Equations for E_m and E_s . Several simplifying assumptions are made in deriving the equations for E_m and E_s , as shown in Appendix A. These assumptions may result in inaccurate results, for some cases, in comparison with the results from more rigorous computer analysis or scale model tests. The inclusion of correction factors into the equations of 14.5 practically eliminates the inaccuracy (within certain ranges for the various parameters) for most practical grid designs.

When using the equations of 14.5, the following limits are recommended for square grids, or for rectangular grids having the same number of conductors in both directions:

$$n \leq 25$$

$$0.25 \text{ m} \leq h \leq 2.5 \text{ m}$$

$$d < 0.25 h$$

$$D > 2.5 \text{ m}$$

Although the equations of 14.5 have been tested for n greater than 25 and found to be sufficiently accurate, the tests were not extensive enough to form solid conclusions. Thus, caution should be exercised before exceeding the limits given above.

Furthermore, for equally spaced rectangular grids (that is, with square meshes), the value of n for use on determining the mesh voltage factor K_m and the irregularity factor K_i (using Eqs 68 and 69) should be the geometric mean of the number of conductors in either direction. That is,

$$n = \sqrt{n_A n_B} \quad \text{for calculating } E_m \quad (\text{Eq 79})$$

when n_A and n_B are the number of conductors in each direction. The value of n for use in determining the step voltage factor K_s and the irregularity factor K_i (Eqs 69, 74, and 75) should be the maximum of n_A and n_B .

$$n = \max(n_A, n_B) \quad \text{for calculating } E_s \quad (\text{Eq 80})$$

14.9 Use of Computer Analysis in Grid Design. There are several reasons that may justify the use of more accurate computer algorithms in designing the grounding system. These reasons include:

- (1) One or more of the geometric parameters exceed the limits described above
- (2) A two-layer soil model is required due to significant variations in soil resistivity
- (3) An unsymmetrical grid (that is, L-shaped, with projections, etc) makes it impractical to predetermine the location of the worst touch voltage
- (4) Uneven grid conductor or ground rod spacings cannot be analyzed using the approximate methods of 14.5
- (5) More flexibility in determining local danger points may be desired

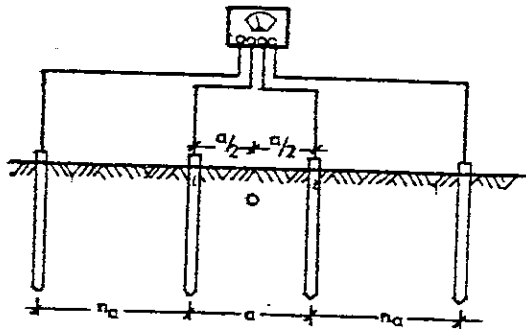


FIGURA Nº 61

ción de las mediciones efectuadas.

cuales mostrarán distintas tendencias en cada caso, en la fig.62, se muestran algunas curvas típicas de distintos tipos de suelos. Para el diseño de una puesta a tierra, sin embargo necesitamos de obtener un único valor de resistividad, equivalente a la combinación de resistividades del terreno estudiado, por esta razón, en cada caso será necesario hacer una interpretación

4.3.12.3 Interpretación

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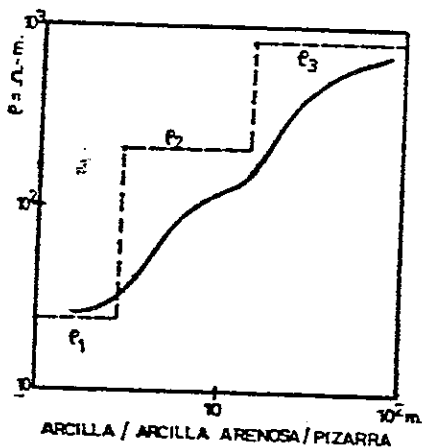
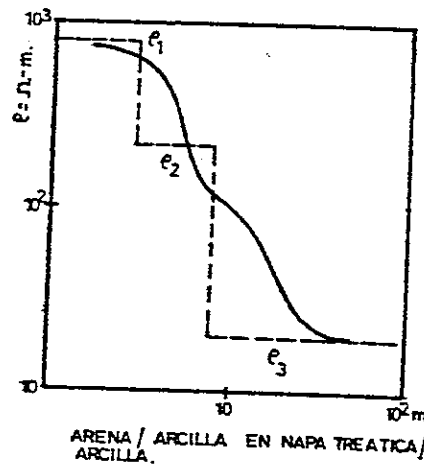
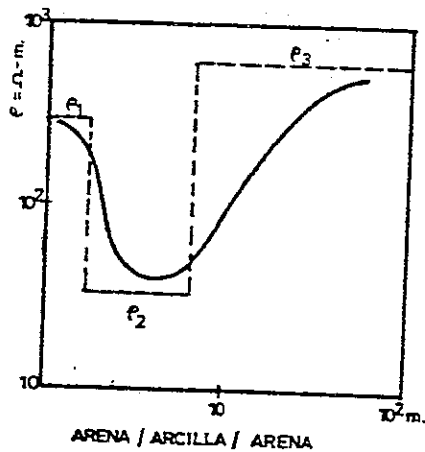
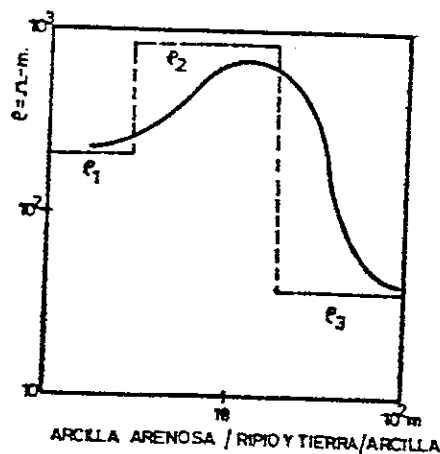


FIG. Nº 62



(A) TABLA No 16
OBTENCION DE Km, KI y KI'

D metros	f (D, d)															
	DIAMETRO Y SECCION DE LOS CONDUCTORES DE MALLAS (mm y mm ²)															
	5,2	7,3	8,1	9,1	9,4	10,5	11,8	13,3	15,2	16,9	18,4	20,6				
	21	27	34	42	53	67	85	107	127	152	202	253				
0,5	0,2565	0,2028	0,1850	0,1664	0,1623	0,1442	0,1260	0,1072	0,085	0,068	0,055	0,037				
1	0,4774	0,4238	0,406	0,387	0,384	0,365	0,347	0,328	0,306	0,289	0,276	0,259				
1,5	0,5064	0,5528	0,535	0,516	0,513	0,494	0,475	0,457	0,435	0,418	0,405	0,387				
2	0,688	0,644	0,627	0,608	0,604	0,586	0,568	0,549	0,527	0,510	0,496	0,479				
2,5	0,769	0,715	0,698	0,679	0,675	0,657	0,639	0,620	0,598	0,581	0,567	0,550				
3	0,833	0,773	0,756	0,737	0,733	0,715	0,697	0,678	0,656	0,639	0,625	0,608				
3,5	0,876	0,822	0,805	0,786	0,782	0,764	0,746	0,723	0,705	0,689	0,674	0,657				
4	0,919	0,865	0,847	0,829	0,825	0,806	0,788	0,769	0,747	0,730	0,717	0,699				
4,5	0,956	0,902	0,885	0,866	0,862	0,844	0,826	0,807	0,785	0,768	0,754	0,737				
5	0,9896	0,936	0,918	0,900	0,896	0,877	0,859	0,840	0,818	0,801	0,788	0,770				
5,5	1,02	0,966	0,949	0,930	0,926	0,908	0,890	0,871	0,849	0,832	0,818	0,801				
6	1,046	0,994	0,979	0,958	0,954	0,935	0,917	0,898	0,876	0,859	0,846	0,828				
7	1,097	1,043	1,025	1,007	1,003	0,984	0,966	0,947	0,925	0,908	0,895	0,877				
8	1,139	1,086	1,068	1,049	1,046	1,027	1,009	0,990	0,969	0,951	0,937	0,920				
9	1,177	1,123	1,105	1,087	1,083	1,064	1,046	1,027	1,005	0,988	0,975	0,957				
10	1,21	1,16	1,139	1,120	1,117	1,098	1,080	1,061	1,039	1,022	1,009	0,991				
15	1,339	1,286	1,268	1,249	1,246	1,227	1,209	1,19	1,168	1,151	1,138	1,120				
20	1,431	1,379	1,359	1,341	1,337	1,319	1,30	1,282	1,259	1,243	1,229	1,212				
25	1,502	1,448	1,431	1,412	1,408	1,390	1,371	1,353	1,331	1,314	1,300	1,283				

n	f(n)	KI	KI'
1	-0,0918	—	—
2	-0,1496	0,994	1,2922
3	-0,1921	1,166	1,5158
4	-0,2256	1,338	1,7394
5	-0,2533	1,51	1,963
6	-0,2769	1,682	2,1866
7	-0,2973	1,854	2,4102
8	-0,3157	2,026	2,6338
9	-0,3320	2,198	2,8574
10	-0,3468	2,37	3,081
11	-0,3603	2,542	3,3046
12	-0,3728	2,714	3,5282
13	-0,3844	2,886	3,7518
14	-0,3952	3,058	3,9754
15	-0,4058	3,23	4,199
16	-0,4148	3,402	4,4226
17	-0,4238	3,574	4,6462
18	-0,4322	3,746	4,8698
19	-0,4404	3,918	5,0934
20	-0,4480	4,09	5,317

LOS VALORES DE Km ESTAN CALCULADOS PARA UNA MALLA CON LOS CONDUCTORES ENTERRADOS A UNA PROFUNDIDAD h = 0,6 mls.
LOS DATOS DE ENTRADA A LA TABLA "A" SON D = DISTANCIA ENTRE CONDUCTORES DE LA MALLA Y d = DIAMETRO DEL CONDUCTOR DE LA MALLA.
EL DATO DE ENTRADA A LA TABLA "B" ES n = NUMERO DE CONDUCTORES PARALELOS EN EL SENTIDO DEL LADO MENOR.

Km SE OBTIENE COMO : $Km = f(D, d) \cdot f(n)$ [véase que los valores de f(n) son negativos]
KI y KI' SE OBTIENEN DIRECTAMENTE.

TABLA N° 17
OBTENCION DE K_S %

[illegible]

TABLA Nº 18
OBTENCION DE K1 y K2*

Superficie de la malla "S" m ²	A/B (RAZON ENTRE LARGO Y ANCHO DE LA MALLA)									
	1		2		3		4		5	
	K ₁	K ₂	K ₁	K ₂	K ₁	K ₂	K ₁	K ₂	K ₁	K ₂
40	1,168	4,685	1,124	4,63	1,08	4,58	1,036	4,52	0,992	4,47
60	1,208	4,808	1,164	4,74	1,12	4,66	1,076	4,59	1,032	4,52
80	1,232	4,88	1,168	4,80	1,144	4,71	1,10	4,63	1,056	4,55
100	1,248	4,93	1,204	4,84	1,16	4,75	1,116	4,66	1,072	4,57
150	1,273	5,01	1,229	4,91	1,185	4,81	1,141	4,7	1,097	4,60
200	1,288	5,05	1,244	4,95	1,2	4,84	1,156	4,73	1,112	4,62
250	1,299	5,08	1,255	4,97	1,211	4,86	1,167	4,75	1,123	4,64
300	1,306	5,11	1,262	4,99	1,218	4,88	1,174	4,76	1,130	4,65
350	1,312	5,13	1,268	5,01	1,224	4,89	1,180	4,77	1,136	4,65
400	1,317	5,14	1,273	5,01	1,229	4,90	1,185	4,78	1,141	4,66
450	1,321	5,15	1,277	5,03	1,233	4,91	1,189	4,79	1,145	4,66
500	1,324	5,16	1,28	5,04	1,236	4,92	1,192	4,79	1,148	4,67

-* ESTAS TABLAS ESTAN CALCULADAS PARA MALLAS CON LOS CONDUCTORES ENTERRADOS A UNA PROFUNDIDAD $h = 0,6 \text{ m.}$

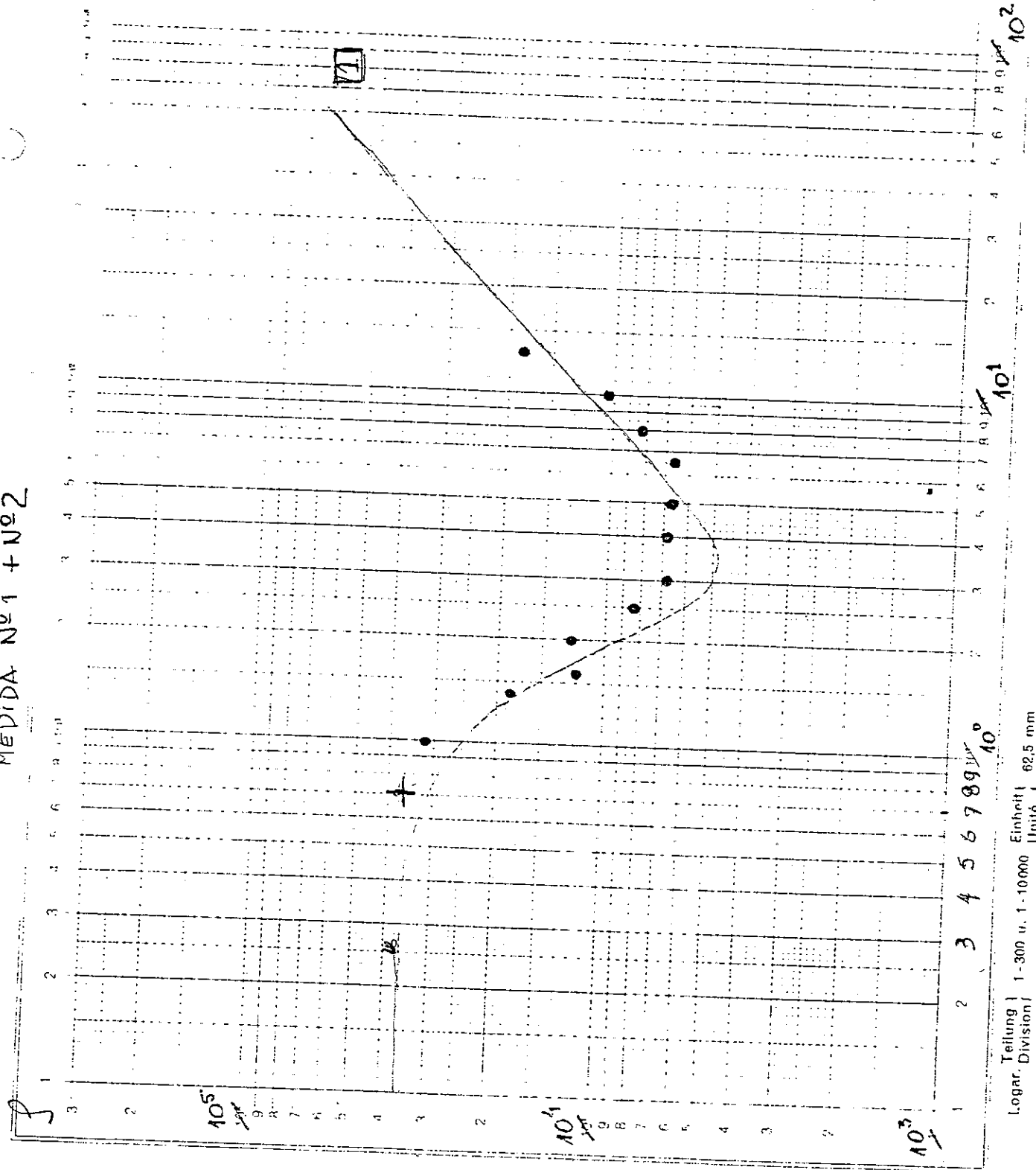
Tabla No.1 Medidas de resistividad

Medida	Electrodo de Corriente	Electrodo de Potencial	Resistividad
	[m]	[m]	[$\Omega.m$]
1	1	0.3	31112
2	1.3	0.3	18664
3	1.6	0.3	11962
4	2	0.3	12549
5	2.5	0.3	8030
6	3	0.3	6764
7	4	0.3	6997
8	5	0.3	6782
9	6.5	0.3	6622
10	8	0.3	8365
11	10	0.3	10284
12	13	0.3	17953

MEDIDA Nº 1 + Nº 2

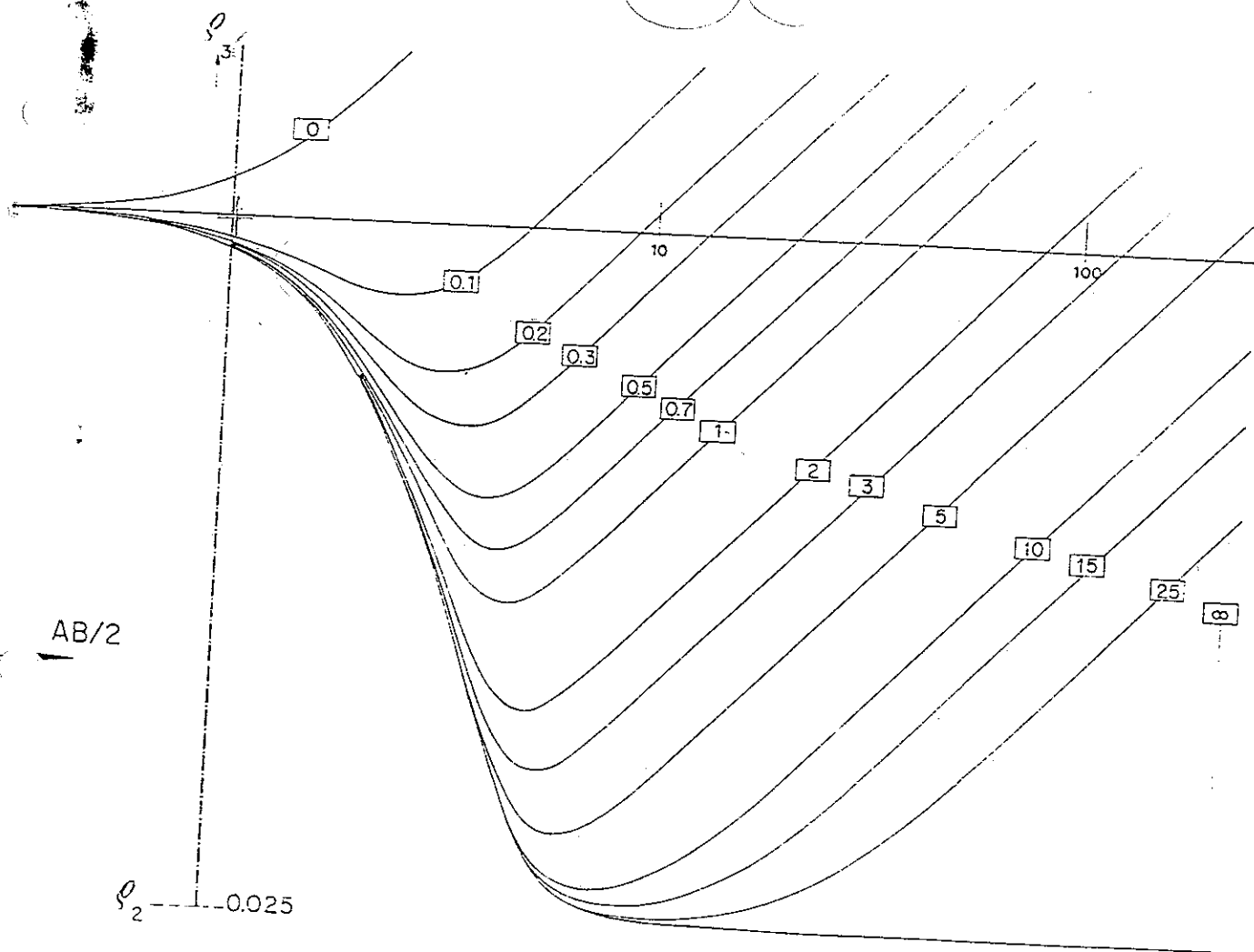
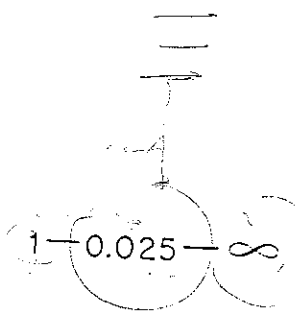
04/02/98

H + 25
1 - 0.025 - ∞



Teilung | 1-300 u. 1-10000 Einheit | 62.5 mm
Logar. Division | Unité |

H-25



$$F = 11.9 = 1.5 = \dots$$

METODO SIMPLIFICADO DE REDUCCION DE CAPAS DE BURGSDORFF - YAKOBS DE UNA MODELACION MULTI CAPAS A UNA CAPA

PROYECTO :

Superficie de la malla

$S := 96$ [metros^2]

Profundidad de enterramiento

$b := 0.6$ [metros]

Numero de capas

$n := 3$

$i := 1..n$

Capa

Resistividad

Profundidad

i

$\rho_i :=$

$h_i :=$

1
2
3

36000
900
999999999

0.2
1 + 0.2
999999999

La profundidad de la capa i se obtiene sumando el espesor de las capas anteriores.

999999999=Infinito

REDUCCION DE LA CAPA SUPERIOR:

$i := 1..n$

$$r := \sqrt{\frac{S}{\pi}}$$

$$r0 := \sqrt{r^2 - b^2}$$

$$q\delta := \sqrt{2 \cdot r \cdot (r + b)}$$

$$V_i := \sqrt{0.5 \cdot \left[q\delta^2 + (h_i)^2 + (r0)^2 - \sqrt{\left[q\delta^2 + (h_i)^2 + (r0)^2 \right]^2 - 4 \cdot q\delta^2 \cdot (r0)^2} \right]}$$

$$F_i := \sqrt{1 - \left(\frac{V_i}{r0} \right)^2}$$

$$F_n := 1$$

$$\frac{F_n}{\sum_i \left[\frac{1}{\rho_i} \cdot (F_i - F_{i-1}) \right]} = 5704.43$$

[$\Omega \cdot \text{metro}$]

Resistividad EQUIVALENTE.

CALCULO DE RESISTENCIA DE MALLA PLANA

Autor :

trabajo:

archivo:

A := 12

Lado mayor de la malla en metros

B := 8

s := A · B Lado menor de la malla en metros

s = 96

Superficie cubierta por la malla en metros²

h := 0.6

Profundidad de enterramiento del reticulado en metros

$$K1 := 1.43 - 2.3 \cdot \frac{h}{\sqrt{s}} - 0.044 \cdot \frac{A}{B}$$

K1, K2 factores que dependen de la configuración de la malla, en el caso de mallas rectangulares se dispone de estas formulas

$$K2 := 5.5 - 8 \cdot \frac{h}{\sqrt{s}} - \left(0.15 \cdot \frac{h}{\sqrt{s}} \right) \cdot \frac{A}{B}$$

ρ := 5704.43

Resistividad EQUIVALENTE

L := 116

Longitud total del conductor que conforma el reticulado en metros

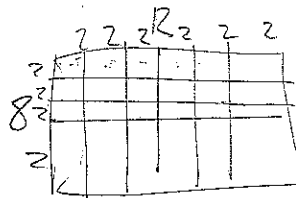
d := $\frac{10.5}{1000}$

Diámetro (mts.) del conductor del reticulado 2/0 AWG

$$R1 := \frac{\rho}{L} \cdot \left(\ln \left(2 \cdot \frac{L}{\sqrt{d \cdot h}} \right) + K1 \cdot \frac{L}{s} - K2 \right)$$

R1 = 219.4236

Para el reticulado



**CORRIENTE DE CORTOCIRCUITO MONOFASICO CONSIDERANDO
LA RESISTENCIA DE LA MALLA**

$$VB := 23 \cdot 10^3 \quad SB := 100 \cdot 10^6 \quad \text{Datos de la Empresa}$$

$$IB := \frac{SB}{\sqrt{3} \cdot VB} \quad IB = 2.5102 \cdot 10^3 \quad ICCant := 635$$

$$ZB := \frac{VB^2}{SB} \quad ZB = 5.29$$

$$Rpt := 219.4236 \quad loant := \frac{\frac{ICcant}{3}}{IB} \quad loant = 0.0843 \text{ (pu)}$$

$$Rf := \frac{Rpt}{ZB} \quad Rf = 41.4789 \text{ (pu)}$$

$$2Z1 + Zo = Zfant \quad Zf_ant := \frac{1}{loant} \quad Zf_ant = 11.859 \text{ Corresponde a la impedancia de falla del sistema.}$$

$$locorregido := \frac{1}{Zf_ant + 3 \cdot Rf} \quad locorregido = 0.0073$$

$$I_falla_nuevo := 3 \cdot locorregido \cdot IB$$

$$I_falla_nuevo = 55.2522 \text{ (A)} \quad \text{considera efecto de la malla}$$

CALCULO DE LOS VOLTAJES MAXIMOS DE PASO Y DE CONTACTO

Proyecto: .

Autor :

Metodo desarrollado en IEEE Guide for Safety in AC substation grounding en pag. 112
"Calculation of maximum Step and Mesh Voltages"

$$\rho := 5704.43$$

Resistividad EQUIVALENTE [Ohms-m]

$$I_g := 55.2522$$

Corriente que circula por la malla..... [A]

$$h := 0.6$$

Profundidad de enterramiento de la malla [m]
LADO MAS LARGO DE LA MALLA

$$L1 := 12$$

Longitud lado mas largo de la malla [m]

$$D1 := 2$$

Espacio entre conductores paralelo
..... [m]

$$L2 := 8$$

LADO MAS CORTO DE LA MALLA
Longitud lado mas corto de la malla [m]

$$D2 := 2$$

Espacio entre conductores paralelo
..... [m]

$$n1 := \text{ceil}\left(\frac{L1}{D1}\right)$$

$$n2 := \text{ceil}\left(\frac{L2}{D2}\right)$$

$$D1 := \frac{L1}{n1}$$

$$D2 := \frac{L2}{n2}$$

$$D1 = 2$$

$$n1 = 6$$

Distancia corregida entre cond. lado mas largo
Número de conductores lado mas largo

$$D2 = 2$$

$$n2 = 4$$

Distancia corregida entre cond. lado mas corto
Número de conductores lado mas corto

$$L_c := (n1 + 1) \cdot L2 + (n2 + 1) \cdot L1$$

$$L_c = 116$$

Longitud total conductores horizontales[m]

$$L_r := 0$$

Longitud total de las barras[m]

$$d := \frac{10.5}{1000}$$

Diámetro del conductor de la malla (metros), 2/0 AWG

Voltaje de contacto

$$K_{ii} := \frac{1}{(2 \cdot n1)^{\left(\frac{2}{n1}\right)}}$$

Si la malla tiene barras en el perimetro, o para mallas con barras en las esquinas, entonces $K_{ii}=1$

$$h_o := 1$$

Profundidad de referencia de la malla (metros)

$$K_h := \sqrt{1 + \frac{h}{h_o}}$$

$$L := L_c + 1.15 \cdot L_r$$

$$K_i := 0.656 + 0.172 \cdot n1$$

$$K_m := \frac{1}{(2 \cdot \pi)} \cdot \left[\ln \left[\frac{D1^2}{(16 \cdot h \cdot d)} + \frac{(D1 + 2 \cdot h)^2}{(8 \cdot D1 \cdot d)} - \frac{h}{(4 \cdot d)} \right] + \frac{K_{ii}}{K_h} \cdot \ln \left[\frac{8}{(\pi \cdot (2 \cdot n1 - 1))} \right] \right]$$

$$E_m := \frac{\rho \cdot \lg \cdot K_m \cdot K_i}{L}$$

Voltaje de paso

$$K_s := \left(\frac{1}{\pi} \right) \cdot \left[\frac{1}{(2 \cdot h)} + \frac{1}{(D1 + h)} + \frac{1}{D1} \cdot [1 - 0.5^{(n1 - 2)}] \right]$$

Valido para profundidades de enterramiento de la malla comprendida en el rango:
 $0.25 < h < 2.5$ metros

$$E_s := \frac{\rho \cdot \lg \cdot K_s \cdot K_i}{L}$$

Resumen de valores calculados:

$$K_{ii} = 0.4368$$

$$K_h = 1.2649$$

$$K_i = 1.688$$

$$K_m = 0.6292$$

$$K_s = 0.5369$$

Longitud total de conductor de cobre

$$L_c = 116 \quad [\text{m}]$$

Voltaje de contacto máximo esperado

$$E_m = 2886 \quad [\text{Volts}]$$

Voltaje de paso máximo esperado

$$E_s = 2462 \quad [\text{Volts}]$$

DETERMINACION DE VOLTAJES DE PASO, CONTACTO ADMISIBLES Y LARGO TOTAL DE CONDUCTOR DE LA MALLA

Metodo desarrollado en "IEEE Guide for safety in AC substation grounding
ANSI/IEEE Std. 80-1986, pag 46

TITULO : Proyecto
AUTOR :
ARCHIVO :

Gravillado (piedra molida):

$\rho_s := 12000$ [$\Omega \cdot \text{metros}$] Resistividad de la gravilla
 $h_s := 0.4$ [metros] Profundidad de la capa de gravilla
 Terreno : $\rho := 5704.43$ [$\Omega \cdot \text{metros}$] Resistividad EQUIVALENTE
 Tiempo : $t := 0.6$ [segundos] Duracion de la corriente de choque.

$n := 1 \dots 100$

$$K := \frac{\rho - \rho_s}{\rho + \rho_s}$$

El valor de 100 iteraciones da una buena presicion de la serie infinita.

$$C_s := \left(\frac{1}{0.96} \right) \cdot \left[1 + 2 \cdot \sum_n \left[\frac{K^n}{\sqrt{1 + \left(\frac{2 \cdot n \cdot h_s}{0.08} \right)^2}} \right] \right]$$

C_s : Factor de reduccion que ajusta la resistividad nominal de la capa superficial.

$C_s := \text{if}(\rho = \rho_s, 1, C_s)$

Si la capa superficial tiene la misma resistividad de la capa de la malla, entonces $C_s=1$

$C_s = 0.979$

VOLTAJE DE CONTACTO: [Volts]

Peso 50 kilos $(1000 + 1.5 \cdot C_s \cdot \rho_s) \cdot \frac{0.116}{\sqrt{t}} = 2788$

Peso 70 kilos $(1000 + 1.5 \cdot C_s \cdot \rho_s) \cdot \frac{0.157}{\sqrt{t}} = 3773$

VOLTAJE DE PASO:

Peso 50 kilos $(1000 + 6 \cdot C_s \cdot \rho_s) \cdot \frac{0.116}{\sqrt{t}} = 1 \cdot 10^4$

Peso 70 kilos $(1000 + 6 \cdot C_s \cdot \rho_s) \cdot \frac{0.157}{\sqrt{t}} = 14484$