

# Development of A Software based on IEEE 80-2000 Standards and Available on Android Devices, to Design Ground Meshes in High Voltage Substations

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**Abstract**— This application was designed and programmed for the efficient design of the ground mesh protection system to safeguard the lives of people, animals and vegetation, as well as the useful life of each of the elements found in an electrical substation. This is based on the IEEE 80 - 2000 standard, which gives us a guide for safety in AC substations. The professional in charge of the project and who will use the application, must use the Wenner method to obtain a maximum number of measurements equal to 7, and for each measurement it must be repeated 3 times; With this, the application will indicate if the terrain is homogeneous or heterogeneous. As a second step, the application will calculate the gauge of the conductor that will be used in the real area where this protection system will be implemented. After this, the application will find the step and touch voltage values (important parameters in this type of protection system). And finally, the electrical resistance of the mesh, the total number of rods to be used, among other data, will be calculated. At the end of all these steps, the application provides a report where all the values found and necessary for the implementation of the mesh are found. Said report will be saved in the internal memory of the device in which the application is starting.

**Keywords**—Ground mesh, IEEE 80-2000, application, touch and step voltages, Wenner's method

## I. INTRODUCTION

In the Engineering area, specifically in Electrical Engineering, there are various points of electricity generation, which is transported by high voltage lines and also elevated or reduced in substations. In the latter, there are large power transformers; It is due to these machines and their high cost, that designers find it necessary to implement the ground mesh protection system, in order to guarantee efficient work of the machines and of course, preserve and safeguard the lives of all living things. As mentioned above, there are various standards to comply with this, but the one chosen for the construction of the application is the IEEE 80 - 2000 standard, which provides us with a methodology to design ground meshes in

substations, this with various formulas, graphs, tables, etc. Despite this, there are some professionals in the field who do not follow this or any other guide for the design of this protection system, that is, they do not make a preliminary study of the terrain and only assume values such as resistance, resistivities, heights, among other parameters., which can lead to inefficient work and in the worst case, the death of those involved and mentioned above. [1]

## II. FUNCTION OF THE APPLICATION

### A. Define the type of terrain

The application will show spaces to complete resistance values obtained by the user through measurements with the Wenner method (maximum 7). In case the user makes fewer measurements, there will be no need to complete them with zero since the measurements not completed will not affect the subsequent calculation. The application will calculate the resistivity values based on the values entered by the user and through the following formulas.

$$\rho = 2\pi aR \quad (1)$$

$$\rho = 4\pi aR / [1 + (2a/\sqrt{a^2 + 4b^2}) - (2a/\sqrt{4a^2 + 4b^2})] \quad (2)$$

The criteria to know which formula to use in the resistivity calculation will be the following:

$$a > 20*b \quad (3)$$

Where:

a: distance between electrodes

b: dipstick burial depth

$\rho$ : apparent resistivity

R: resistance value

If equation 3 is fulfilled, the application will solve the first one, otherwise the second one[6].

In projects that use earth mesh protection systems, it must be considered that there are two types of land: Homogeneous and Heterogeneous.

Homogeneous Soils to those that present a very similar resistivity in all their measurements regardless of the depth at which the measurement is made.

Heterogeneous Soils are those that present a different resistivity between their measurements and that consequently infinite layers are generated with different values and at certain depths.

Making an analogy between the current and the types of terrain, we could suggest that a homogeneous terrain would behave like a continuous current since it presents equal values over time.

Similarly, a heterogeneous terrain would approach alternating current since it is a variant. Various theses show that in Peru heterogeneous soils abound more than homogeneous ones, so a criterion must be had to analyze said soils without neglecting the layers below the earth. That is why the IEEE 80-2000 standard proposes an analysis of the first two layers below the finished floor level, that is, the first layer will have a resistivity value  $\rho_1$  at a certain height H, for the next layer it will be considered only the resistivity  $\rho_2$  since its height will be considered infinite.

With the above mentioned:

The relationship that will define the type of terrain on which the measurements have been made is as follows[1]:

$$\text{Terrain indicator} < 0.3 \text{ (for homogeneous terrain)} \quad (4)$$

The terrain indicator formula is defined as follows:

$$(\text{Maximum resistivity}/\text{Minimum resistivity}) - 1 \quad (5)$$

Where:

Maximum and minimum resistivity value calculated in the first stage of the application

The application will show a graph constructed from the data inserted by the user, so that the user can select which of the two curves predetermined by the application it resembles. Once selected, the application will show the value of  $\rho_1$

Following this, two measurements of apparent resistivities must be selected, with this the application will graph two curves in which the user must locate the intersection to obtain the values of the height h of  $\rho_1$  and the constant "k".

With these data the application calculates  $\rho_2$

$$\rho_2 = (-\rho_1 * (K+1)) / (K-1) \quad (6)$$

As a next step, the application will show us a window with a list of materials that are used on the finished floor level. Then the user must enter the value of the depth of the mesh.

## B. Calculation Of Conductor Gauge

The user enters the value of the symmetric fault current, which is the maximum short – circuit current, in kilo amperes (short-circuit current of the system allows to establish the characteristics of the protection elements that must withstand or cut the fault current, so that it is necessary to perform the calculation for each of the voltage levels of the system)[7]. The duration of the ground fault current in seconds according to the electrical concessionaire and the ambient temperature of the design, these parameters are important since the gauge of the conductor cable must withstand them in order to maintain continuity of service.

The IEEE 80-2000 standard proposes different types of cables which are at the user's choice for the design of the grounding mesh.

After choosing between the different types of cables, the application will calculate the appropriate gauge through the following formula:

$$A_{\text{mm}}^2 = I_F / \sqrt{(T_{\text{cap}} * 10^{-4} / \alpha_r * t_s * \rho_r) * \text{Ln} ((K_0 + T_m) / (K_0 + T_a))} \quad (7)$$

Where:

$I_F$  = symmetric fault current (Amperes)

$T_a$  = ambient temperature

$T_m$  = Maximum Allowable Temperature in ° C

$K_0$  = thermal coefficient of conductivity

$T_{\text{cap}}$  = thermal capacity per unit volume

$\alpha_r$  = Factor at 20 ° C

$\rho_r$  = Thermal coefficient of resistivity at reference temperature  $T_r$  in 1 / ° C

$t_s$  = duration of fault current

## C. Tolerable Stress Criterion

At this stage, two important factors must be calculated, which are directly related to the safety of people, these factors are step and touch voltage.

The term touch voltage refers to the potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded Structure[2]

Likewise, the tension of step, when current is flowing from an overhead conductor through a chain-link fence to the earth, a high-voltage condition is created and a voltage gradient will occur based on the resistivity of the soil, resulting in a voltage difference – also known as a potential difference – between two points on the ground. This is called a step potential as it can cause voltage difference between a person's feet.

These values are calculated according to the IEEE 80-2000 standard with the following formulas

$$E_{p50} = (1000 + 6 * C_s * \rho_s) * 0.116 / \sqrt{t_s} \quad (8)$$

$$E_{p70} = (1000 + 6 * C_s * \rho_s) * 0.157 / \sqrt{t_s} \quad (9)$$

$$E_{t50} = (1000 + 1.5 * C_s * \rho_s) * 0.116 / \sqrt{t_s} \quad (10)$$

$$E_{t70} = (1000 + 1.5 * C_s * \rho_s) * 0.157 / \sqrt{t_s} \quad (11)$$

The subscripts 50 and 70 refer to the average body mass of the workers who are usually close to the area where the mesh is buried to earth[5]

But these formulas involve a surface layer reduction factor, this factor is calculated as follows:

$$C_s = 1 - ((0.09 * (1 - \rho / \rho_s)) / (2 * h_s + 0.09)) \quad (12)$$

Where:

$\rho$  = apparent resistivity

$\rho_s$  = resistivity of surface material

$h_s$  = Thickness of surface material

We also note that the numerator is the apparent resistivity of the ground that, if it were heterogeneous, would be calculated with the following formula

$$\rho_a = (L_r * \rho_1 * \rho_2) / ((\rho_2 * (H - h)) + \rho_1 * (L_r + h - H)) \quad (13)$$

Where:

$\rho_1$  and  $\rho_2$  = top and bottom layer resistivity respectively

$H$  = Thickness of surface material (meters)

$h$  = mesh burial depth (meters)

$L_r$  = vertical rod length (2.4 m)

If it is homogeneous, the apparent resistivity will be equal to the average resistivity

#### D. Design of mesh

The application contemplates 3 forms of mesh design: square, rectangular and in the shape of an "L".

When choosing the square mesh, the value of the mesh side in meters must be entered, in addition to the vertical and horizontal separation distance ( $D_y$  and  $D_x$  respectively), if it were rectangular, it is the same procedure, only the length ( $L_x$ ) and width ( $L_y$ ) values must be entered of the mesh, since in this case both sides would not be the same as it is in the square mesh.

If it were the case of an "L" shaped mesh, you must enter greater and lesser length and width values, that is, 4 values and their respective separation distances.

After having entered these values, the application will calculate:

- Number of vertical conductors (M):

$$M = L_y / D_y \quad (14)$$

- Number of horizontal conductors (N):

$$N = L_x / D_x \quad (15)$$

- Conductor length through perimeter (P):

$$P = L_x + L_y \quad (16)$$

- Mesh area (A):

$$A = L_x * L_y \quad (17)$$

- Number of ground rods (electrode):

$$N_c = 0.9 * \sqrt{A} \quad (18)$$

- Total length of ground rods ( $L_e$ ):

$$L_e = N_c * 2.4 \quad (19)$$

- Total length of buried conductor ( $L_c$ ):

$$L_c = N * L_x + M * L_y \quad (20)$$

- Total length of buried conductors and rods ( $L_t$ ):

$$L_t = L_c + L_e \quad (21)$$

- And most important parameter, the resistance of the mesh:

$$R = \rho * [(1/L_T) + (1/\sqrt{20A}) * (1 + 1/(1+h\sqrt{20/A}))] \quad (22)$$

#### E. Mesh current and ground potential rise.

To calculate the mesh current, the following formula is used:

$$I_G = I_F * D_f * S_f * C_p \quad (23)$$

Defining each variable:

$I_F$  = symmetric fault current (Amperes)

$D_f$  = decay factor for the entire duration of the failure

$S_f$  = Current division factor

$C_p$  = Growth factor

To calculate all the variables involved in the mesh current, the user will enter the value of the X / R ratio depending on the characteristics of the substation, in addition, the application will allow to choose the approximate equivalent impedances of the power lines guard cables transmission and distribution neutrals. Then, the number of transmission lines and the number of distribution neutrals must be chosen (this last piece of information is one of the most important at this stage, since it allows us to know the exact value of  $S_f$ ). Since only some  $S_f$  values are predetermined for various combinations of

transmission lines and distribution neutrals and in order to know the exact values of  $S_f$  in all possible combinations between number of transmission lines and distribution neutrals, for this application the following formula was solved:

$$S_{f(x,y)} = |(Z_{eq}(x,y) / R_g + (Z_{eq}(x,y))| \quad (24)$$

But to know the equivalent impedance value of an uncommon combination of transmission lines and distribution neutrals, for example 1 and 3 for a  $r_{tg}$  of 15 ohm and  $r_{dg}$  of 25 ohms, it was interpolated taking as an upper limit the values of combination 1 - 2 and 1 - 4, thus the equivalent impedance was calculated and replaced in the formula 22. This was the criterion for calculating the value of  $S_f$ .

After entering the X / R value, choose the RTG or RDG value and select the combination of number of transmission lines and distribution neutrals; the user must answer the question: Do you consider the total capacity of the substation and in the future keep the load and feeders constant?

If the answer is affirmative, the value of  $C_p$  will be equal to 1, since the load will remain constant over time and the total area of the substation is being considered without projections to increase. Otherwise, to a negative answer, the user must enter the percentage (for example 15%) in which he plans to increase the total capacity of area or load, then  $C_p$  will be calculated with the following formula[5]:

$$C_p = 1 + [(C\%) / 100] \quad (25)$$

The variable  $D_f$  will be calculated with the following formula:

$$D_f = \sqrt{1 + [T_a * (1 - e^{-2tf/T_a})]/tf} \quad (26)$$

Defining each variable:

$t_f$  = duration of fault current

$T_a$  = time constant of the DC component

$f$  = frequency (Hz)

$$T_a = (X/R) * (1 / 2 * \pi * f) \quad (27)$$

After the application has developed all the implicit formulas within the mesh current, it will show in a partial report, the touch voltage values, symmetric fault current, reduction factor for the entire fault duration, current division factor, mesh current, ground potential rise (GPR).

GPR is equal to the grid resistance times the current maximum grid. Besides, GPR is the maximum electrical which attained relative to a distant grounding point as at the potential of remote earth. [8]

$$GPR = I_G * R \quad (28)$$

$I_G$  : mesh current

$R$  : resistance of the mesh

#### F. Initial design verification

Once the above formulas have been made, IEEE 80-2000 presents us with the following inequality to identify if the preliminary design is correct:

$$GPR < E_{T(50 \text{ o } 70 \text{ Kg})} \quad (29)$$

If expression 29 is true, the application displays the following message:

*correct design, but consider to apply some treatment to reduce the resistance of the mesh to the ground by 80% in case the resistance of the mesh is greater than 1 ohm, in order to respect the measures, set by the ieee-80- regulation 2000.*

As a result of the message mentioned above, the design will culminate showing a final report, this report shows the sections of: Type of terrain, conductor gauge, tolerable tension criteria and mesh resistance. In addition, the final report can be saved on the user's device for future studies or analysis.

But if expression 29 is not fulfilled, the following warning is displayed

*The initial design must be readjusted with factors, please press "continue" to apply correction factors.*

#### G. Designed touch voltage and Actual derived step voltage

Designed touch and step voltages are the voltages obtained from the designed grid system and must be less in value compared to tolerable voltages. If otherwise, the grid system has to be redesigned until the values fall less than the tolerable voltages.[3]

#### H. Designed touch voltage

$$E_m = [\rho * I_G * K_m * K_i] / L_M \quad (30)$$

Defining each variable:

$\rho$  = apparent resistivity

$L_M$  = Effective length buried

$$L_M = L_C + L_e \quad (31)$$

$I_G$  = symmetric fault current (Amperes)

$K_i$  = correction factor for irregularity

$$K_i = 0.644 + 0.148 * n \quad (32)$$

The constant "n" has different sub-values for every kind of mesh considered in this application:

$$n_a = 2 * (L_c / L_p) \quad (33)$$

$$n_b = \sqrt{L_p / (4 \sqrt{A})} \quad (34)$$

$$n_c = [ (L_x * L_y) / A ] \quad (35)$$

- For square meshes:

$$n = n_a$$

- For rectangular meshes:

$$n = n_a * n_b$$

- For L-shaped meshes:

$$n = n_a * n_b * n_c$$

$K_m$  = separation factor for mesh voltage

$$K_m = 1/2\pi * \text{Ln} [ (D^2/16hd) + ((D+2h)^2/8dD) - (h/4d) ] +$$

$$(K_{ii}/K_h) * \text{Ln} [ 8 / \pi * (2n - 1) ] \quad (36)$$

- Where:

h : mesh burial depth

d : conductor diameter

D : distance of greater of the mesh

$$D = \sqrt{(L_x)^2 + (L_y)^2} \quad (37)$$

$$K_{ii} = 1 / (2 * n)^{2/n} \quad (38)$$

$$K_h = (1 + h)^{1/2} \quad (39)$$

Once these factors have been applied, the application should check the following expression:

$$E_m < E_{T(50 \text{ o } 70 \text{ Kg})} \quad (40)$$

If true, the step-by-pass voltage continues. Otherwise, you return to the mesh design stage.

### I. Actual derived step voltage

The value of the real tension of the mesh is obtained by means of the following expression:

$$E_s = [\rho * I_G * K_s * K_i] / L_s \quad (41)$$

Defining each variable:

$\rho$  = apparent resistivity

$L_s$  = Effective length buried

$$L_s = 0.75 * L_c + 0.85 * L_e \quad (42)$$

$I_G$  = symmetric fault current (Amperes)

$K_i$  = correction factor for irregularity (32)

$K_s$  = Space factor for step voltage

$$K_s = (1 / \pi) * [ (1/2h) + (1/D+h) + ((1-0.5^{n-2})/D) ] \quad (43)$$

- Where:

n : constant of (33) or (34) or (35)

h : mesh burial depth

D : distance of greater of the mesh (37)

Once these factors have been applied, the application should check the following expression:

$$E_s < E_{p(50 \text{ o } 70 \text{ Kg})} \quad (44)$$

If true, the application sends the final report. Otherwise, you return to the mesh design stage.

## III. CRITERIA NOT CONTEMPLATED IN IEEE-80-2000

### A. Method for calculating soil resistivity

Since the IEEE-802000 does not include a specific method for calculating soil resistivity, it was necessary to resort to investigating various types of evaluation for it. Concluding in various comparisons, that the most correct method based on theory and calculation is the Tagg method [4].

Tagg, after a thorough study of stratified soils, arrives at the following equation:

$$\rho_a = \rho_1 * (1 + 4 \sum_{n=1}^{n=\infty} (\frac{k_n}{\sqrt{1 + (2n \frac{h}{a})^2}} - \frac{k_n}{\sqrt{4 + (2n \frac{h}{a})^2}})) \quad (45)$$

Known as the Tagg equation, through which I determine some master curves that simply consist of giving values to the variables k, h and a, obtaining values of  $\rho_a / \rho_1$  for each case.

It is necessary to comment that K varies between -1 and 1, that is to say that for K values between -1 and 0, results of  $\rho_a / \rho_1$  greater than 0 and less than 1 are obtained, which corresponds to the fact that the first layer has a resistivity greater than the second. For K values between 0 and 1, the values of  $\rho_a / \rho_1$  will be greater than 1, since the resistivity of the second layer is greater than that of the first.

The reflection coefficient is given by the following equation:

$$K = (\rho_2 - \rho_1) / (\rho_2 + \rho_1) \quad (46)$$

For a better development of the application, the master curves were made using the Desmos software. In this way we obtained exact values to obtain the relation of  $\rho_a / \rho_1$ .

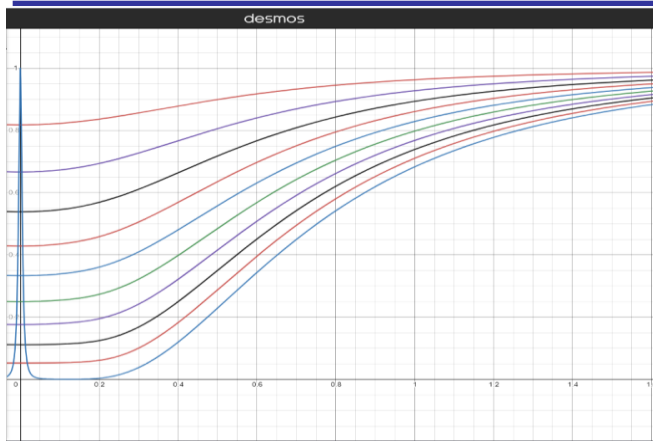


Fig.1 Negative "K" Master Curve

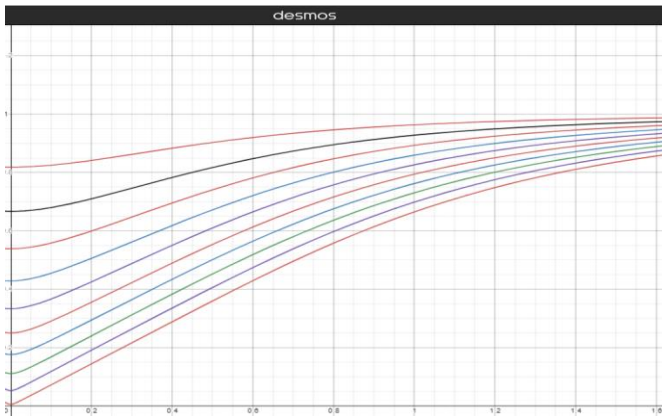


Fig.2 Positive "K" Master Curve

#### IV. CONCLUSION

1. Achieving an optimal design of a ground mesh does not depend solely on the characteristics of the electrodes but is active on the terrain where they are located.
2. In this article we show the development of a software that can be used on a mobile device, which leads to the design of a ground mesh so that in cases of electrical discharges or overvoltage, the current finds a safe route and thus avoid damage to a being alive or nature.
3. The resistance of the mesh depends on the lengths, cross section and shape of the electrodes.
4. The application has been programmed to give as a result the dimensions of the electrodes, touch and step voltages, among other parameters and shown respecting the IEEE 80-2000 standard.
5. At the end of the design, the application will suggest applying a chemical additive with which it will improve the results, this notification will be displayed regardless of whether the results obtained are optimal or not.

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